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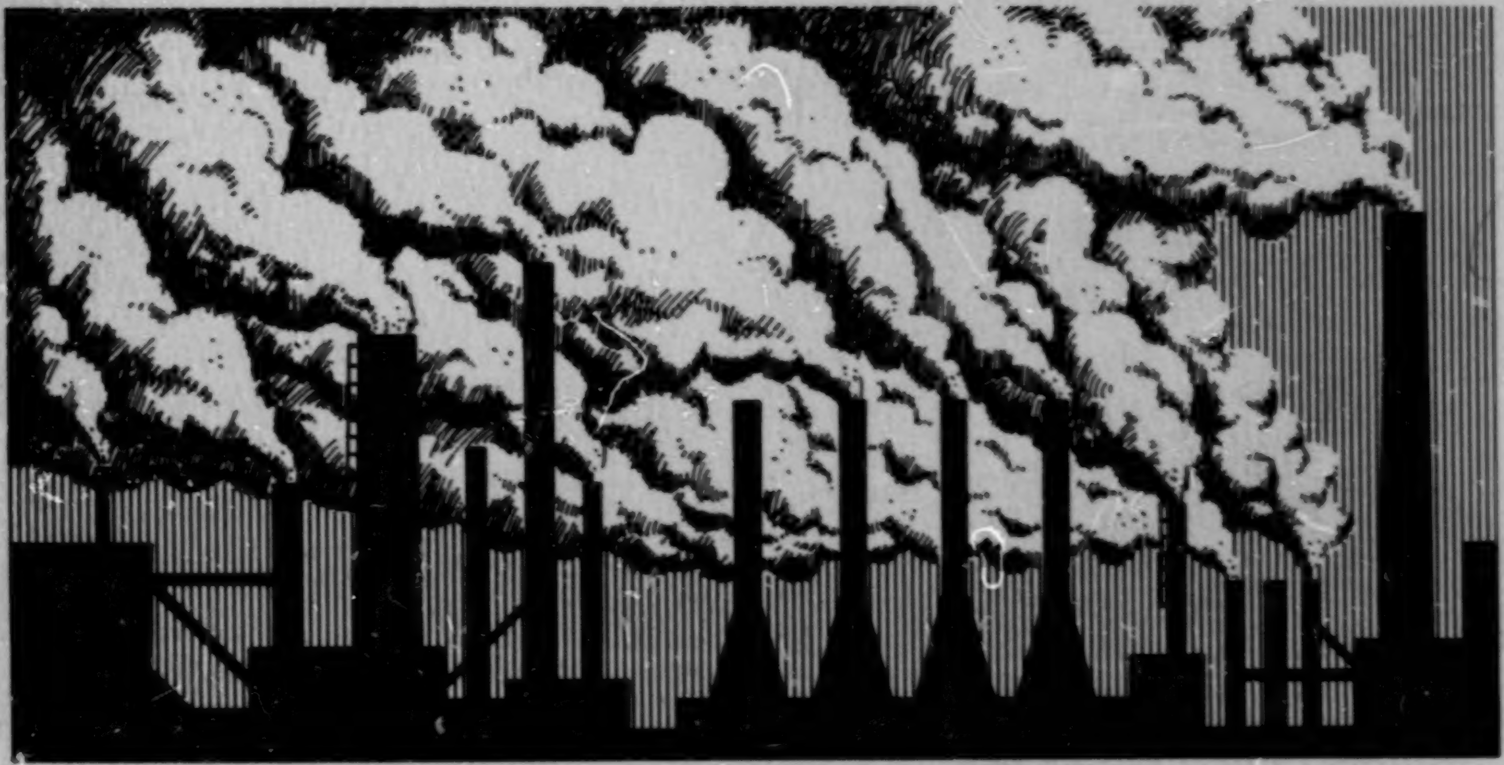

PARTICULATE POLLUTANT SYSTEM STUDY
VOLUME II - FINE PARTICLE EMISSIONS

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16. Abstracts

A program was conducted to quantify fine-particle emissions (0.01-2 microns) from particulate pollution sources. The primary objective was to use the best data currently available (ie., 1969-1970) on particle-size distributions of particulates from uncontrolled and controlled sources, fractional efficiency curves for specific control devices, and the degree of application of control equipment on specific sources to estimate the mass and number of fine particles emitted from particulate pollution sources. Secondary objectives were the assessment of (1) the applicability of standard sampling and particle sizing methods to the fine particle regime, and (2) the current understanding of the adverse effects of fine particulate pollutants. This report presents the results of this study.

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Emission	Ground vehicles
Sources	Aircraft
Air pollution control equipment	Ships
	Railroads

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PARTICULATE POLLUTANT SYSTEM STUDY

Volume II - Fine Particle Emissions

1 August 1971

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MRI Project No. 3326-C

Prepared for

Air Pollution Control Office
Environmental Protection Agency
411 West Chapel Hill Street
Durham, North Carolina 27701

PREFACE

This report was prepared for EPA/APCO under Contract No. CPA-22-69-104, which was monitored by Mr. Don K. Felton and Mr. Robert Lorentz.

The work was conducted in the Environmental Sciences Section of the Physical Sciences Division.

The report was written by Dr. L. J. Shannon and Mr. P. G. Gorman with the assistance of Miss M. Reichel.

Dr. Seymour Calvert and Mr. Paul L. Magill, consultants to MRI, made valuable contributions to this document.

Approved for:

MIDWEST RESEARCH INSTITUTE

H. M. Hubbard, Director
Physical Sciences Division

1 August 1971

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1. Summary

Midwest Research Institute, under contract from the Air Pollution Control Office, Environmental Protection Agency, conducted a program to quantify fine-particle emissions (0.01-2 μ) from particulate pollution sources. The primary objective was to use the best data currently available (i.e., 1969-1970) on particle-size distributions of particulates from uncontrolled and controlled sources, fractional efficiency curves for specific control devices, and the degree of application of control equipment on specific sources to estimate the mass and number of fine particles emitted from particulate pollution sources. Secondary objectives were the assessment of (1) the applicability of standard sampling and particle sizing methods to the fine particle regime, and (2) the current understanding of the adverse effects of fine particulate pollutants.

1.1 Data Acquisition and Analysis

The MRI data bank and data acquisition activities conducted during the study provided information on particle-size distributions and fractional efficiency characteristics. Particle-size data were found to be quite extensive for some sources, but rather meager for other sources. Coal-fired power plants, cement kilns, lime kilns, and foundries are in the former category, while sources in primary and secondary nonferrous metallurgy, iron and steel, and pulp and paper industries fall in the latter category.

Another facet of the particle-size distribution data is that a significant portion, approximately 85%, was obtained from uncontrolled sources. The lack of particle-size data from controlled sources clearly indicates that neither control equipment manufacturers nor air pollution control agencies have placed any significant emphasis on the particle size of pollutants emitted from control equipment. The main thrust of air pollution control to date has been toward control on a mass basis, with no concern given to the size and number of particles emitted from the control equipment.

Analysis of the particle-size distribution data indicated that a major portion (over 95%) had been obtained by sampling and sizing procedures that are not suitable for the particle size range < 2 μ. As a result, only a meager quantity of accurate data is available on particle size, in the < 2 μ size range, for effluents from either controlled or uncontrolled sources.

Evaluation of fractional efficiency information for control devices revealed that limited data are available, and an assessment of the reliability of much which is available is hampered by lack of specifics pertaining to source sampling, particle sizing, and source operating methods.

In many cases the reported fractional efficiency curves were only identified as "typical" for a certain type of device with no other information, comment, or reference. Also, fractional efficiency data pertaining to a specific control device on a specific industrial source are very limited. However, in general, the fractional efficiency data did reflect the expected efficiency characteristics of specific types of control devices. That is, multiclones showed a higher efficiency curve than cyclones, and Venturi scrubbers exhibited a higher efficiency than low-pressure drop scrubbers. Detailed discussions of fractional efficiency and particle size data are presented in Sections 5 and 6, pages 25 and 37.

1.2 Fine-Particle Emissions (1969-1970)

The method used to calculate the mass and number of fine particles emitted from a source utilized:

1. Production figures and emission factors reported in Volume I.[1]

2. Particle-size distributions for particulates emitted by uncontrolled sources.

3. Percent application of control on specific sources, with a breakdown of this percent application of control into the percent application of each type of control device.

4. Fractional efficiency characteristics of each type of control device.

To calculate the number of particles emitted in each particle-size range, the following assumptions were made:

1. The particles are all spherical in shape, and

2. The density of the particles is independent of particle size.

With these assumptions the equation relating mass and number emissions is

$$(\text{Mass})_{d_1-d_2} = \frac{\rho\pi(d_{m.p.})^3}{6} N$$

where

$(\text{Mass})_{d_1-d_2}$ = mass emitted in particle-size range between diameter d_1 and d_2

ρ = particle density

$d_{m.p.}$ = particle diameter midpoint between d_1 and d_2

N = number of particles emitted with average diameter $d_{m.p.}$

Procedures for estimating both mass and number emissions are presented in detail in Section 7.0.

Since, in general, particle-size distributions from uncontrolled sources and fractional efficiency curves were not available in the 0.01-2 μ range, it was necessary to extrapolate available data to this size range. A linear extrapolation was performed by plotting data on log-probability coordinates. A limited check of the validity of the extrapolation procedure is presented in Section 7.1. The limited particle-size data for specific pollution sources made it impossible to provide more than a general indication of the mass of fine particles emitted from some sources.

Tables 1 and 2 summarize the estimates of fine-particle emissions on the basis of mass and number of emitted particles. The emission totals shown in Tables 1 and 2 are based on 1968 production data and 1969-1970 application of control information reported in Volume I.1/ Also, in computing the fine-particle emissions shown in Tables 1 and 2, and the total mass emissions given in Table 4.1.1 of Volume I,1/ control equipment on sources was assumed to be in operation 100 percent of the plant operating time. It is recognized that this is not actually the case. However, accurate data are not available on the percentage of time that control equipment are in use on industrial sources. The emission figures given in Tables 1 and 2 and Table 4.1.1, Volume I, are therefore conservative.

Because of the lack of adequate data on many specific process sources, the emission figures given in Tables 1 and 2 are not complete for some industry categories. Also, fine-particle emissions for several sources (e.g., crushed stone operations) could not be calculated for each size range shown in Tables 1 and 2 because of incomplete particle size distribution data. Furthermore, fine-particle emissions from potentially significant industrial categories such as grain and feed mills, primary nonferrous metallurgy, food processing and clay products could not be estimated because of incomplete data. These deficiencies are discussed in more detail in Section 7.

Fine-particle emissions from the industrial sources listed in Table 1 are estimated to be at least 4 x 10^6 tons/yr. This represents approximately 20-25 percent of the total mass emissions from these sources.1/

TABLE 1

FINE-PARTICLE EMISSION FROM INDUSTRIAL SOURCES
(Mass Basis, 10^3 Tons/Year)

Source	Fine Particle Size Ranges (Microns)						Reliability
	1-3	0.5-1.0	0.1-0.5	0.05-0.1	0.01-0.05	Total	Rating+
1. Stationary Combustion							
A. Coal							
1. Electric Utility							
a. Pulverized	591.6	178.6	99.2	2.9		872.3	1
b. Stoker	21.7	5.7	2.2			29.6	1
c. Cyclone	48.2	13.9	7.3	0.2		69.6	1
Total from Electric Utility						971.5	
2. Industrial							
a. Pulverized	15.1	0.5				15.6	3
b. Stoker	56.6	7.3	2.1			66	3
c. Cyclone	13.5	6.7	4.1	0.1		24.4	3
Total from Industrial Coal						106	
B. Fuel Oil							
1. Electric Utility and Industrial	126.9					126.9	3
C. Natural Gas and LPG							
1. Electric Utility and Industrial	97.2					97.2	3
Total from Fuel Oil and Gas						224.1	
Total from Fuel Combustion						1,301.6	
2. Crushed Stone	740.4	92.9	34.7			868	5
3. Iron and Steel							
A. Sinter Machines	3.8	1.2	0.6			5.6	3
B. Open Hearth Furnace*	60-80	20-56	8.5-234	0.1-22	0-3.6	108-376	4
C. Basic Oxygen Furnace*	0.9	18.9	153.7	1.0		174.5	3
D. Electric Arc Furnace	3.8	2.5	5.2	1.3	1.5	14.3	3
Total from Iron and Steel						302.4-570.4	
4. Kraft Pulp Mills							
A. Bark Boilers	49.1	11.9	6.5	0.3		67.8	3
B. Recovery Furnace**	95.3	78	74.7	1.4		249.4	3
C. Lime Kiln	1.6	0.2				1.8	4
Total from Kraft Pulp Mills						319	
5. Cement Plants, Rotary Kilns	130.8	32.7	13.5			177	2
6. Hot-Mix Asphalt Plants							
A. Rotary Dryer	96.4	36.3	21.5			154.2	3
B. Ventline	14.4	1.7	0.2			16.3	3
Total from Hot-Mix Asphalt Plants						170.5	
7. Ferroalloys							
A. Electric Furnace	18.4	27.8	81.1	17.3	7.7	152.3	3
B. Blast Furnace	0.8					0.8	3
Total from Ferroalloys						153.1	
8. Lime Plants							
A. Rotary Kilns	40.6	18.8	23.6	3.0	1.8	87.8	2
B. Crushing and Screening***	25-99					25	4
Total from Lime Plants						113	

TABLE 1 (Concluded)

	Fine Particle Size Ranges (Microns)						Reliability
Source	1-3	0.5-1.0	0.1-0.5	0.05-0.1	0.01-0.05	Total	Rating+
9. Secondary Nonferrous Metallurgy****	127					127	5
10. Carbon Black	93					93	3
11. Coal Preparation Plants, Thermal Dryer	63.5					63.5	4
12. Petroleum FCC Units	45					45	4
13. Municipal Incinerators	10.4	6.7	11.5	3.5	4.3	36.4	2
14. Fertilizer, Granulators and Dryers	7.1	3.5	3.1			13.7	3
15. Iron Foundries, Cupolas	6.8	2.4	3.1	0.4	0.4	13.1	2
16. Acids							
A. Sulfuric	2.7					2.7	4
B. Phosphoric (thermal)	1.0					1.0	4
		Total from Acids				3.7	
		Total from Major Industrial Sources				3,800-4,068	

---

* See Section 7.2.3 for discussion of calculations.

** See Section 7.2.4 for discussion of calculations.

*** See Section 7.2.8 for discussion of calculations.

**** See Section 7.2.9 for discussion of calculations.

+ Reliability rating is indicative of the relative reliability of the emission quantities. Ratings range from 1 to 5 with 1 being the most reliable.

Note: Potentially significant sources not evaluated because of lack of sufficient data: (1) operations related to agriculture, (2) primary nonferrous metallurgy, (3) clay products, (4) food processing operations, and (5) fiberglass manufacture.

TABLE 2

FINE PARTICLE EMISSIONS FROM INDUSTRIAL SOURCES
(Number Basis, Particles/Year)

Source	Fine Particles Size Range (Microns) 1-3	0.5-1.0	0.1-0.5	0.05-0.1	0.01-0.05	Total
1. Stationary Fuel Combustion						
A. Coal						
1. Electric Utility						
a. Pulverized	5.1×10^{22}	29.5×10^{22}	250×10^{22}	480×10^{22}		765×10^{22}
b. Stoker	0.2×10^{22}	0.9×10^{22}	5.6×10^{22}			6.7×10^{22}
c. Cyclone	0.42×10^{22}	2.3×10^{22}	18.5×10^{22}	83×10^{22}		104×10^{22}
2. Industrial						
a. Pulverized	0.3×10^{22}	0.08×10^{22}				0.38×10^{22}
b. Stoker	0.5×10^{22}	1.2×10^{22}	5.6×10^{22}			7.3×10^{22}
c. Cyclone	0.12×10^{22}	1.1×10^{22}	10.4×10^{22}	42×10^{22}		53.6×10^{22}
B. Fuel Oil						
1. Electric Utility and Industrial	1.1×10^{22}					1.1×10^{22}
C. Natural Gas						
1. Electric Utility and Industrial	0.85×10^{22}					0.85×10^{22}
			Total from Stationary Combustion			939×10^{22}
2. Crushed Stone	6.8×10^{22}	16.2×10^{22}	94.6×10^{22}			117.6×10^{22}
3. Iron and Steel						
A. Sinter Machines	2.74×10^{20}	16.5×10^{20}	128×10^{20}			147.2×10^{20}
B. Steel-Making Furnaces						
1. Open Hearth	$2.62\text{-}3.48 \times 10^{21}$	$16.2\text{-}45.8 \times 10^{21}$	$109\text{-}3{,}000 \times 10^{21}$	$0.83\text{-}180 \times 10^{23}$	$0\text{-}4.6 \times 10^{25}$	$2.1\text{-}670 \times 10^{23}$*
2. Basic Oxygen	5.6×10^{20}	22.2×10^{21}	2.82×10^{24}	1.08×10^{25}		3.92×10^{24}
3. Electric Arc	2.1×10^{20}	26.4×10^{20}	8.5×10^{22}	1.37×10^{24}	24.7×10^{24}	26.2×10^{24}
			Total from Iron and Steel			$3\text{-}9.7 \times 10^{25}$
4. Kraft Pulp Mills						
A. Bark Boiler	4.25×10^{21}	19.6×10^{21}	167×10^{21}	500×10^{21}		69×10^{22}
B. Recovery Furnace	8.25×10^{21}	129×10^{21}	19.2×10^{23}	23.4×10^{23}		44×10^{23}
C. Lime Kiln	1.4×10^{20}	3.3×10^{20}				4.7×10^{20}
			Total from Kraft Pulp Mills			50.9×10^{23}
5. Cement Plants	9.7×10^{21}	46.4×10^{21}	3×10^{23}			3.6×10^{23}
6. Hot-Mix Asphalt Plants						
A. Rotary Dryer	8×10^{21}	57.5×10^{21}	5.3×10^{23}			6×10^{23}
B. Secondary Sources	1.2×10^{21}	2.7×10^{21}	4.95×10^{23}			4.4×10^{21}
			Total from Asphalt Plants			6×10^{23}

TABLE 2 (Concluded)

Source	Fine Particle Emissions (Microns)					Total
	1-3	0.5-1.0	0.1-0.5	0.05-0.1	0.01-0.05	
7. Ferroalloys						
A. Electric Furnace	1.33×10^{21}	37×10^{21}	17.3×10^{23}	2.3×10^{25}	16.5×10^{25}	19×10^{25}
B. Blast Furnace	5.8×10^{19}					5.8×10^{19}
			Total from Ferroalloys			19×10^{25}
8. Lime Plants						
A. Rotary Kiln	3.14×10^{21}	27.6×10^{21}	5.4×10^{23}	4.4×10^{24}	4.1×10^{25}	46×10^{24}
B. Crushing and Screening	1.93×10^{21}					1.93×10^{21}
			Total from Lime Plants			46×10^{24}
9. Secondary Nonferrous Metallurgy	7.85×10^{21}					7.85×10^{21}
10. Carbon Black	1×10^{22}					1×10^{22}
11. Coal Preparation Plants, Thermal Dryers	3.9×10^{21}					3.9×10^{21}
12. Petroleum FCC Units	3.7×10^{21}					3.7×10^{21}
13. Municipal Incinerators	9×10^{20}	11×10^{21}	3×10^{23}	5.8×10^{24}	11×10^{25}	11.6×10^{25}
14. Fertilizer	7.7×10^{20}	72×10^{20}	9.95×10^{22}			10.7×10^{22}
15. Iron Foundries, Cupolas	5.25×10^{20}	35.3×10^{20}	7.1×10^{22}	5.9×10^{23}	9.2×10^{24}	9.9×10^{24}
16. Acids						
A. Sulfuric	3.4×10^{20}					3.4×10^{20}
B. Phosphoric	1.2×10^{20}					1.2×10^{20}
			Total from Acids			4.6×10^{20}
			Total from Major Industrial Sources			$40.2\text{-}46.9 \times 10^{25}$

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* See Section 7.2.3 for discussion of calculations.

On a mass basis, stationary combustion, crushed stone, iron and steel, and kraft pulp mills are significant industrial sources of fine-particle pollutants.

Table 1 also includes an indication of the reliability of emission quantities presented in Tables 1 and 2. The reliability was determined from an evaluation of data on (1) mass emission factors; (2) overall efficiency of control equipment; (3) extent of application of control; (4) fractional efficiency for control devices; (5) particle-size distribution; and (6) production figures. The evaluation considered the quantity of data available, a comparison of data from different information sources, and the source of the data. Ratings range from 1 to 5 with 1 being the most reliable.

As shown in Table 2, metallurgical furnaces and municipal incinerators are significant sources of fine-particle pollutants on a number basis. In view of the many assumptions involved in the calculations, the individual emission quantities given in Tables 1 and 2 are considered to be only a "first-cut" estimate.

Differences were found in the estimated fine-particle and total mass emissions from some sources that emit mainly micron or submicron particulates. In these cases, the estimated fine-particle emissions exceeded the total mass emissions. Section 7.2 presents these results in detail.

Table 3 presents a source priority ranking, based on the mass and number of fine particles emitted, of the industrial sources for which adequate information was available to estimate emissions. The priority ranking indicates those sources where initial efforts should be focused to control the emission of fine-particulate pollutants. In our opinion, improved control of fine-particle emissions from the high priority sources would result in a significant reduction in the mass and/or number of fine particulates emitted from stationary sources.

TABLE 3

PRIORITY RANKING OF INDUSTRIAL SOURCES OF FINE-PARTICULATE POLLUTANTS

1. Ferroalloy Furnaces
2. Steel-Making Furnaces
3. Coal-Fired Power Plants
4. Lime Kilns
5. Kraft Pulp Mill Recovery Furnaces
6. Municipal Incinerators
7. Iron Foundry Cupolas
8. Crushed Stone Plants
9. Hot-Mix Asphalt Plants
10. Cement Kilns

To indicate the relative magnitude of the fine particulate problem from stationary sources, fine-particle emissions were also estimated for mobile and miscellaneous sources. Particulate emissions from mobile sources were assumed to be uncontrolled and to consist of all $< 2\ \mu$ particulates. Table 4 summarizes the estimate of fine-particle emissions from these sources. Table 5 presents an estimate of fine-particle emissions from miscellaneous sources for which adequate particle size data were available. Fine-particle emissions from natural dusts, forest fires, and agricultural burning could not be estimated because of lack of reliable particle size data.

1.3 Projections of Fine-Particle Emissions

Projections were made of fine-particle mass and number emissions through the year 2000 for some of the sources listed in Tables 1 and 2. Because of incomplete data it was not possible to project the emissions of primary and secondary nonferrous metallurgy, petroleum, acids, and carbon black manufacturing operations.

1.3.1 Mass basis: Two methods were used to project the mass of fine particles emitted in future years.

TABLE 4

FINE-PARTICLE EMISSIONS FROM MOBILE SOURCES

Source	Emissions (tons/year)
1. Motor Vehicles	
a. Gasoline	420,000
b. Diesel	260,000
2. Aircraft	30,000
3. Railroads	220,000
4. Water Transport	150,000
5. Nonhighway Use	
a. Agriculture	79,000
b. Commercial	12,000
c. Construction	3,000
d. Other	26,000
Total	1,200,000

TABLE 5

FINE-PARTICLE EMISSIONS FROM MISCELLANEOUS SOURCES

Source	Emissions (tons/year)
1. Rubber from tires	300,000
2. Cigarette smoke	230,000
3. Ocean salt spray	340,000
4. Aerosol from spray cans	390,000
Total	1,260,000

Method 1 - The projection of emissions by Method 1 assumes that there will be no change in the net control for a source. This assumption results in an increase in emissions in proportion to increases in production capacity. Production figures were projected by the same methods outlined in Volume I[1/] and were used to proportionally increase the current mass of fine-particle emissions.

Method 2 - The projection of emissions by Method 2 takes into account the increases in production but two assumptions are also made:

1. All sources will be controlled by 1980, i.e., application of control will reach 100 percent by 1980.

2. Increased utilization of the most efficient control devices will continuously increase the efficiency of control on fine particles so that by the year 2000 it will be equivalent to controlling all sources with baghouses. The fabric filter was selected as a reference standard of performance because it is one of the most efficient devices currently available for collecting fine particulates. It seems realistic to assume that improvements in the other control devices and possible development of new devices would allow the efficiency of control devices, in the year 2000, to match the performance capability of the best devices that are presently available.

No attempt was made to account for any changes in particle size distributions of emitted particulates that might result from process modifications in future years.

The two projection methods represent two extremes: no improvement in control versus stringent control. An intermediate position is more probable, but projection of an intermediate situation requires information regarding the percent application of each type of control device on specific sources in the future years. Of course, this information is not available, and to project emissions, gross assumptions would have to be made regarding future equipment utilization. Projections involving gross assumptions of future equipment utilization were not deemed valuable.

Table 6 summarizes the projections of fine-particle emissions on a mass basis. Details of the calculation procedures are given in Section 8.1, pages 119 to 123. Fine-particle emissions for the sources listed in Table 6 can be reduced from 3.5×10^6 tons/year (1968 emission level) to 3.5×10^5 tons/year by the year 2000 if the efficiency of control on all these sources in the year 2000 is equivalent to the performance of the best device currently available (i.e., baghouse). The projections also show that, even if stringent control is achieved in the year 2000, coal-fired power plants, basic oxygen furnaces, and kraft-pulp-mill recovery furnaces will each emit over 50,000 tons/year of $< 2\ \mu$ particulate.

1.3.2 Number basis: The number of fine particles emitted by stationary sources to the year 2000 were projected by two methods that are extensions of the techniques used to project mass emissions. The first method assumes no change in net control which means that the emissions on a number basis, as they were on a mass basis, are directly proportional to future production capacities. Method 2 utilizes the mass emissions projected by the second technique discussed in Section 1.3.1 and an assumption regarding the average diameter of fine particles emitted from sources in the future. The average diameter of the particles emitted in 1968 could be computed from the mass emissions versus particle size data given in Table 1. However, some method had to be devised to determine an average diameter for the years between 1968 and 2000. This was accomplished by computing an average diameter for the fine particles emitted in the year 2000 when all sources were assumed to be controlled by baghouses or their equivalent. The average fine-particle diameters for the intervening years between 1968 and 2000 were taken from a straight line interpolation between the average size of the fine particles emitted in 1968 and in 2000. The sequence of calculation steps for Method 2 is presented in detail in Section 8.2, page 123.

Table 7 presents a summary of the projections of fine-particle emissions on a number basis. The projections show that ferroalloy electric furnaces, rotary lime kilns in lime plants, municipal incinerators, coal-fired power plants, and steel-making furnaces (BOF and electric arc) will be significant sources of fine-particle pollutants, on a number basis, even in the year 2000.

1.4 Literature Surveys

Literature surveys were conducted in the areas of source sampling techniques for fine particles, particle size measuring methods, and adverse effects of fine particulate pollutants. Information from the literature surveys, coupled with data from personal contacts with university and APCO research groups, testing laboratories, and consultants, was used to prepare summaries of the state of knowledge in each area. These

TABLE 6

PROJECTIONS OF FINE-PARTICLE EMISSIONS FROM INDUSTRIAL SOURCES
(Mass Basis, 10^6 Tons/Year)

		Year						
Source	Method	1970	1975	1980	1985	1990	1995	2000
I. Stationary Combustion								
A. Coal								
1. Electric Utility	I	1.046	1.201	1.374	1.600	1.864	2.110	2.388
	II	0.976	0.883	0.731	0.653	0.528	0.335	0.090
2. Industrial	I	0.133	0.150	0.170	0.170	0.170	0.166	0.164
	II	0.127	0.111	0.084	0.064	0.043	0.023	0.002
II. Crushed Stone	I	1.067	1.389	1.814	2.300	2.934	3.715	4.713
	II	1.046	1.186	1.137	1.090	0.933	0.606	0.033
III. Iron and Steel								
A. Sinter Machines	I	0.006	0.007	0.008	0.009	0.009	0.010	0.010
	II	0.006	0.006	0.005	0.004	0.003	0.002	0.000
B. Open Hearth Furnace	I	0.372	0.252	0.169	0.098	0.056	0.001	0.000
	II	0.325	0.141	0.040	0.018	0.008	0.000	0.000
C. Basic Oxygen Furnace	I	0.188	0.293	0.454	0.515	0.581	0.618	0.654
	II	0.177	0.235	0.305	0.277	0.237	0.170	0.094
D. Electric Arc Furnace	I	0.015	0.018	0.021	0.023	0.026	0.029	0.034
	II	0.014	0.010	0.004	0.004	0.004	0.003	0.003
IV. Kraft Pulp Mills								
A. Bark Boilers	I	0.074	0.089	0.109	0.115	0.123	0.142	0.165
	II	0.070	0.069	0.063	0.051	0.037	0.022	0.002
B. Recovery Furnace	I	0.267	0.314	0.372	0.407	0.446	0.514	0.594
	II	0.257	0.256	0.268	0.208	0.163	0.116	0.051
C. Lime Kilns	I	0.002	0.002	0.003	0.003	0.003	0.004	0.004
	II	0.002	0.002	0.002	0.001	0.001	0.001	0.000
V. Cement Plants, Rotary Kilns	I	0.188	0.227	0.273	0.319	0.372	0.421	0.476
	II	0.175	0.164	0.140	0.125	0.101	0.062	0.016
VI. Hot Mix Asphalt Plants, Dryers	I	0.168	0.205	0.250	0.305	0.375	0.460	0.563
	II	0.158	0.158	0.152	0.141	0.117	0.074	0.018
VII. Ferroalloy Electric Furnaces	I	0.155	0.166	0.180	0.198	0.219	0.241	0.267
	II	0.131	0.074	0.008	0.009	0.010	0.011	0.012
VIII. Lime Plants, Rotary Kilns	I	0.103	0.134	0.174	0.189	0.206	0.311	0.466
	II	0.095	0.094	0.086	0.071	0.053	0.044	0.016
IX. Coal Preparation Plants, Thermal Dryer	I	0.071	0.086	0.105	0.124	0.145	0.166	0.190
	II	0.066	0.061	0.047	0.043	0.037	0.025	0.011
X. Municipal Incinerators	I	0.040	0.051	0.061	0.071	0.081	0.095	0.109
	II	0.037	0.037	0.031	0.027	0.021	0.014	0.003
XI. Fertilizer, Granulators, and Dryers	I	0.015	0.016	0.017	0.019	0.021	0.023	0.025
	II	0.014	0.012	0.010	0.008	0.006	0.004	0.001
XII. Iron Foundries, Cupolas	I	0.013	0.015	0.016	0.017	0.017	0.018	0.019
	II	0.012	0.010	0.006	0.005	0.003	0.002	0.003
Totals	I	3.92	4.61	5.57	6.48	8.45	9.04	10.84
	II	3.69	3.51	3.12	2.8	2.3	1.51	0.355

TABLE 7

PROJECTIONS OF FINE-PARTICLE EMISSIONS FROM INDUSTRIAL SOURCES

(Number Basis, 10^{23} Particles/Year)

		Year						
Source	Method	1970	1975	1980	1985	1990	1995	2000
I. Stationary Combustion								
A. Coal								
1. Electric Utility	I	94.3	108.3	123.9	144.2	168.1	190.3	215.3
	II	94.0	97.1	89.3	88.8	80.3	57.2	17.4
2. Industrial	I	7.66	8.64	9.81	9.81	9.81	9.62	9.50
	II	7.60	7.65	6.98	5.79	4.33	2.45	0.46
II. Crushed Stone	I	14.5	18.8	24.6	31.2	39.8	50.3	63.9
	II	14.2	18.2	23.6	27.5	29.1	23.7	1.6
III. Iron and Steel								
A. Sinter Machines	I	0.172	0.224	0.291	0.316	0.346	0.521	0.782
	II	0.152	0.165	0.171	0.148	0.121	0.076	0.015
B. Open Hearth Furnaces	I	663	449	302	174	101	1.0	0.0
	II	633	275	84	40	19	0.0	0.0
C. Basic Oxygen Furnaces	I	42.3	65.9	101.9	115.6	130.5	138.8	147.0
	II	40.5	53.8	69.8	63.4	54.2	38.9	21.5
D. Electric Arc Furnaces	I	280	330	390	427	469	540	624
	II	257	198	89	89	90	93	89
IV. Kraft Pulp Mills								
A. Bark Boilers	I	7.5	9.0	11.0	11.7	12.6	14.5	16.8
	II	7.5	8.3	8.6	7.7	6.4	4.3	0.37
B. Recovery Furnaces	I	47	55	65	72	79	91	105
	II	46	49	54	44	37	28	13
C. Lime Kilns	I	0.005	0.006	0.007	0.008	0.008	0.010	0.011
	II	0.005	0.005	0.006	0.005	0.004	0.003	0.001
V. Cement Plant Rotary Kilns	I	3.8	4.6	5.5	6.5	7.6	8.6	9.7
	II	3.7	4.2	4.0	4.1	3.7	2.6	0.8
VI. Hot-Mix Asphalt Plants, Dryers	I	6.5	8.0	9.7	11.9	14.6	17.9	21.9
	II	6.2	6.4	6.3	6.1	5.2	3.4	0.9
VII. Ferroalloy Electric Furnaces	I	1,940	2,070	2,240	2,470	2,740	3,000	3,320
	III	1,720	1,140	140	150	170	190	210
VIII. Lime Plants, Rotary Kilns	I	538	699	911	989	1,080	1,630	2,440
	II	530	601	616	564	484	461	192
IX. Coal Preparation Plants, Thermal Dryers	I	0.004	0.005	0.007	0.008	0.009	0.010	0.012
	II	-	-	Not Calculated		-	-	-
X. Municipal Incinerators	I	1,260	1,610	1,940	2,250	2,570	3,030	3,480
	II	1,180	1,320	1,130	1,060	890	610	140
XI. Fertilizer, Granulators, and Dryers	I	1.14	1.25	1.36	1.48	1.62	1.77	1.94
	II	1.08	1.00	0.85	0.74	0.59	0.37	0.07
XII. Iron Foundries, Cupolas	I	100	110	121	127	132	138	145
	II	96	88	62	57	50	34	6
Totals	I	5,006	5,548	6,258	6,842	7,556	8,862	10,600
	II	4,637	3,868	2,385	2,208	1,924	1,549	693

summaries are presented in Appendices A, B, and C. The highlights of the appendices are presented in the following sections.

1.4.1 Particulate sampling and sizing: Standard collecting techniques are inadequate for collecting particulate pollutants for accurate particle size determinations, particularly for particles 1 μ or smaller. Cyclone separators tend to break up aggregates and friable particles, stainless steel or alundum thimbles do not quantitatively capture the submicron particles, and small particles may penetrate deeply into the body of a fiber filtering medium before they are captured and then cannot be removed for subsequent analyses.

A sampling device which collects submicron particles and causes neither formation nor breakup of aggregates is necessary if accurate particle size information is to be obtained. Cascade impactors, thermal precipitators, and small electrostatic precipitators are devices currently available that come close to meeting these requirements, and are clearly superior to the standard sampling trains. A cascade impactor which can be inserted inside a duct is the most versatile of these devices. Stainless steel cascade impactors are now available which permit "in-stack" collection of submicron particles.

If a standard sampling train is used to collect particulates for subsequent particle sizing, failure to disperse the particles adequately as discrete particles will be a major source of error. The use of cascade impactors, thermal precipitators, or electrostatic precipitators as sampling devices minimizes the redispersion problem because optical sizing techniques are generally used in conjunction with these devices.

The Bahco Micro-Particle Classifier has been used extensively for routine particle size measurements, and a major portion of the data currently available on the particle size of particulates emitted from industrial sources has been obtained by using this device. The range of applicable particle diameter for the Bahco instrument is 6 to 60 μ. As a result of the extensive use of the Bahco method, only a meager quantity of accurate data is available on the particle size of particulate pollutants in the < 2 μ size range.

1.4.2 Adverse effects of particulates on human health: The adverse effects caused by particulate pollutants on human health are, for the most part, related to injury to the surfaces of the respiratory system. Particulate material in the respiratory tract may produce injury itself, or it may act in conjunction with gases, altering their sites or their modes of action. A combination of particulates and gases may produce an effect that is greater than the sum of the effects caused by either individually (i.e., synergistic effect).

Laboratory studies of man and other animals show that the deposition, clearance, and retention of inhaled particles is a very complex process, which is only beginning to be understood. Particles cleared from the respiratory tract may exert effects elsewhere. Available data from laboratory experiments do not provide suitable quantitative relationships for establishing air quality criteria for particulates. These studies do, however, provide valuable information on some of the bio-environmental relationships that may be involved in the effects of particulate air pollution on human health.

Toxicological studies on animals have shown that:

1. Particulate matter may exert a toxic effect via one or more of three mechanisms:

(a) The particle may be intrinsically toxic because of its inherent chemical and/or physical characteristics.

(b) The particle may interfere with one or more of the clearance mechanisms in the respiratory tract.

(c) The particle may act as a carrier of an adsorbed toxic substance.

2. Evaluation of irritant particulates on the basis of mass or concentration alone is not sufficient; data on particle size and number averages per unit volume of carrier gas are needed for adequate interpretation.

3. The toxicological importance to mankind of submicron particles cannot be overemphasized.

4. Particles below 1 μ may have a greater irritant potency than larger particles.

5. A small increase in concentration could produce a greater-than-linear increase in irritant response when the particles are $< 1 \mu$.

6. All particulate matter does not potentiate the response to irritant gases.

7. Both solubility of sulfur dioxide in a droplet and catalytic oxidation to sulfuric acid play a role in the potentiation of sulfur dioxide by certain particulate matter.

The analyses of numerous epidemiological studies clearly indicate an association between air pollution, as measured by particulate matter accompanied by sulfur dioxide, and health effects of varying severity. This association is most firm for the short-term air pollution episodes. The studies concerned with increased mortality also show increased morbidity.

The association between long-term residence in a polluted area and chronic disease morbidity and mortality is somewhat more conjectural. However, in the absence of other explanations, the findings of increased morbidity and of increased death rates for selected causes, independent of economic status, must still be considered consequential.

Information is lacking regarding the mechanisms involved in the enhancement of viral virulence by specific air pollutants. Specific methods by which air pollutants can synergistically affect viral infections are unknown. It is possible that fine particulate matter may act as carriers for certain virus agents.

1.4.3 Modification of the atmosphere by particulates: Suspended fine particles may have considerable influence on the behavior of the atmosphere and thus on human activities. They can act as condensation or freezing nuclei and therby modify weather patterns. They absorb and scatter light and decrease visibility. Fine particles in the atmosphere may also influence solar radiation and interfere with astronomical observations.

Visibility reduction related to air pollution is caused primarily by the 0.1 to 1.0 μ radius particles in the atmosphere. The visibility problem associated with particulate air pollution can be divided into specific smoke plumes and well-aged aerosols. The visual appearance of smoke plumes and visual obscuration by smoke plumes are closely related to the amount of light the plumes scatter in the direction of the viewer from their surroundings and the sun. Consequently, evaluation of plumes by a visual effect is more difficult for nonblack plumes than for black plumes, and depends on plume illuminating and viewing conditions. Because of this, nonblack plumes could be evaluated differently when viewed on different days or viewed from different directions,though their aerosol content has not changed. Furthermore, the size of particles and mass per unit time emitted from the stack, and not the appearance or optical properties of the plume, are more important to the eventual air composition, even though appearance may be aesthetically objectionable.

Recent advances in our knowledge of the size distributions and optical properties of well-aged atmospheric aerosols have resulted in a clearer description of visibility reduction by such aerosols. Theoretical and experimental studies of well-aged aerosols have shown that:

1. Aerosols in the lowest region of the atmosphere (troposphere), whether over urban areas or not, tend to have similar size distributions.

2. A narrow range of particle sizes, usually from 0.1 to 1.0 μ radius, controls the extinction coefficient and thereby visibility.

3. The mass concentration of a well-aged aerosol is approximately proportional to the light scattering coefficients for atmospheric aerosols originating naturally or as the result of man's activity.

The increased emission of fine particles into the atmosphere may cause changes in the delicate heat balance of the earth-atmosphere system, thus altering worldwide climatic conditions. Comparisons at different sites over the world covering periods of up to 50 years suggest that a general worldwide rise in turbidity may be taking place. This may well be indicative of a gradual buildup of worldwide background levels of suspended particulates. The net influence of atmospheric turbidity on surface temperature is uncertain, but the emission of long-lived particles may well be leading to a decrease in world air temperature. As more is learned about the general circulation of the atmosphere and the delicate balance between incoming and outgoing radiation, it seems increasingly probable that small changes such as those occasioned by increasing particle loads in the atmosphere may produce very long-term meteorological effects.

Suspended particulate matter may alter weather patterns. There is evidence that some of the particles introduced into the atmosphere by man's activities can act as nuclei in processes which affect the formation of clouds and precipitation. Investigations of snow and rainstorm patterns indicate that submicroscopic particulates from man-made pollution may be initiating and controlling precipitation in a primary manner, rather than being involved in the secondary process wherein precipitation elements coming from natural mechanisms serve to remove the particles by diffusion, collision, and similar scavenging processes.

2. Introduction

Much of today's atmospheric pollution is smoke and dust of such a size that it falls out or is washed out of the atmosphere within a day or so. A certain portion of the pollution is, however, composed of particles a micron or smaller in diameter. These particles may exist in the atmosphere for long periods of time. The presence in the air of submicron particles of various chemical compositions from man-made sources is of increasing interest to many governmental and scientific groups. The interests of these groups range from upper-atmosphere physics and air pollution control engineering to the protection of human health.

Fine particulates emitted from man's activity contribute significantly to all the major adverse aspects of air pollution. Fine particles can initiate or contribute to problems related to human health, atmospheric physical properties, and/or economics. The effects of particulate matter on human health are, for the most part, related to injury to the surfaces of the respiratory system. Such injury may be permanent or temporary. It may be confined to the surface, or it may extend beyond, sometimes producing functional or other alterations. Particle size, together with specific gravity and chemical nature, largely determine: (1) where particles are deposited in the respiratory system, (2) the fate of the particles after deposition, and (3) to a considerable extent their physiological action. Particulate material in the respiratory tract may produce injury itself, or it may act in conjunction with gases, altering their sites or their modes of action. A combination of particulates and gases may produce an effect that is greater than the sum of the effects caused by either individually (i.e., synergistic effects).

Fine particulate pollutants also affect the physical properties of the atmosphere. The chemical and physical properties of the atmosphere affected include: its electrical properties; its ability to transmit radiant energy; its ability to convert water vapor to fog, cloud, rain, and snow; its ability to damage and to soil surfaces. Concern with atmospheric transmission of radiant energy encompasses the entire electromagnetic spectrum, but of particular concern is the infrared region, as it affects the terrestrial heat balance; the ultraviolet region, as it affects both biological processes and photochemical reactions in the atmosphere; and the visible spectrum, as it affects both our ability to see things, and our need for artificial illumination.

The overall impact of fine particulate pollutants, as well as air contaminants in general, on the aggregate of living things in nature is nearly a total mystery. In any ecosystem, the inhabitants exist in a complex state of interaction among themselves and with the inanimate phases of the environment. This interaction is affected by climate and by chemical and physical inputs to the system. As man has become more knowledgeable in these areas, he has also become increasingly aware of the importance to his well being of the action of fine particles. Not only do they affect his own body in a multitude of ways, but they can have extremely important effects on the plants and animals that constitute his food supply. While our present understanding of this interaction does not permit a quantitative assessment of the overall influence of fine particulates, information is being accumulated which points to many negative features of fine-particulate air pollution.

The particulate pollutant systems study conducted at MRI under APCO sponsorship had as an overall objective the delineation of deficiencies in our knowledge regarding the nature and magnitude of particulate pollutant emissions from stationary sources. During the course of the first year's activity, it became apparent that two of the major unknown areas were the mass and size ranges of fine particles emitted from particulate pollution sources. This first year pinpointed deficiencies in our knowledge with respect to important sources of fine particles, actual particle-size range emitted, and the collection efficiency of control equipment in the small-particle size range.

The present study was initiated to bring into focus the current status of what is known about the fine-particle burden emanating from various particulate pollution sources. The primary objective was to use the best data currently available on particle-size distributions from uncontrolled and controlled sources, control equipment fractional efficiency curves,* and the degree of application of control equipment on specific sources to estimate the present level of fine-particle emissions from particulate pollution sources. Secondary objectives were the assessment of (1) the applicability of standard source sampling and particle sizing methods to the fine-particle regime, and (2) the current understanding of the adverse effects of emitted-fine particulate matter.

The major tasks of this program are discussed in the following sections: (1) data acquisition and analysis (Sections 4 and 5); (2) literature surveys on source sampling methods, particle size measuring techniques, and adverse effects of particulate pollution (Appendices A, B, and C); (3) preparation of summary reports on the literature surveys (Appendices A, B, and C); (4) evaluation of methods of graphical representation of particle-size distribution and control equipment fractional efficiency data (Sections 5 and 6); (5) calculations of weight, number and size ranges of fine particulates emitted from specific sources (Section 7); and (6) projection of fine-particle emissions through the year 2000 (Section 8). Important conclusions are listed in Section 9, and Appendices on source sampling methods, particle size measuring techniques, and adverse effects of particulate pollution, data sources, and emission calculations conclude the report.

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* See Section 3, page 21, for definition.

3. Definitions of Important Terms

Several terms, which may not be familiar to the reader, are used in this report. For ease of reading the report, these terms are defined in this section.

3.1 Fine Particulate and Particle Size

The terms "particulate" and "particle size" are ambiguous unless they are carefully defined. Therefore, prior to initiating the study of fine-particulate emissions, it was necessary to select a definition of a particulate, particle size, and the particle-size range of interest to the program. The principal objective in this study was the estimation of the level of fine-particle emissions from man-made sources. Furthermore, attention was to be focused on primary particulates, and not on secondary particulates formed by subsequent reaction of source effluents in the atmosphere.

The following definition was adopted for the purposes of this study:

> "Fine particulate matter is a material that exists as a solid or liquid in the operating environment of the source and is in the size range of 0.01 to 2 μ in diameter."

The operating environment includes the process equipment and its exhaust stack or pipe. The definition of particle size is unique only for spherical particles. For all other cases, the particle size will be dependent upon the experimental method used. Since in this program emissions were to be estimated from available particle-size distribution data, the particle size is defined by the experimental method utilized to obtain the particle size.

The lower size limit of 0.01 μ was selected from considerations of potential adverse effects of particulates on human health. A review of the literature on health effects and discussions with prominent researchers in the field indicated that a lower limit of 0.01 μ would be reasonable for the purposes of this program (see Appendix B). Selection of the upper size limit of 2 μ was based on a review of literature information relating to the influence of particulates on the modification of the atmosphere. Visibility reduction is primarily caused by the 0.1 to 1 μ radius particles and, in addition, reduction in solar radiation and weather modification are caused by 0.05 to 1 μ radius particles (see Appendix C). A secondary factor in establishing the 2 μ upper limit is the decrease in control-equipment efficiency for < 2 μ diameter material.

3.2 Process Emissions

Process emissions are defined as emissions before and upstream of any control devices.

3.3 Fractional Efficiency of Control Equipment

The fractional efficiency (on a mass basis) of a control device is defined as the efficiency of removal of specific sizes of particles. For example, if a stream contains 10 lb. of 1-μ particulate, and a control device removes 9 lb. of this material, the fractional efficiency of the device at 1 μ is 90%.

3.4 Penetration

Penetration of a specific particle size through a control device is defined as

$$[P]_{d_1} = 1 - [EFF]_{d_1}$$

where

$[P]_{d_1}$ = penetration at diameter d_1

$[EFF]_{d_1}$ = fractional efficiency of control device at particle size of d_1 .

4. Data Acquisition

Information on particle-size distributions of effluents from particulate pollution sources and fractional efficiency curves for control equipment applied to these emission sources was obtained from the MRI data bank[1] and data-acquisition activities conducted during the study. The data bank includes about 3,000 technical articles and reports; 500 stack sampling tests from air pollution control agencies; telephone and personal interview reports from 350-400 industrial, testing laboratory, and control device manufacturer contacts; and communiques from consultants and academic people. This data bank was searched for all pertinent data on particle-size distributions and fractional efficiency curves.

Acquisition of additional particle-size data was an integral phase of the program, and efforts were focused on control device manufacturers, source sampling organizations, and university research groups. We contacted numerous potential data sources, and believe that all significant sources of particle-size data have been exhausted. A complete list of contacts made during the program is given in Appendix D.

The second part of the information-acquisition activity was directed to a literature survey in the areas of source sampling techniques for fine particles, fine particle size measuring methods, and adverse effects of emitted fine particulates. Information from these surveys, coupled with data from personal contacts with university groups, testing laboratories, APCO research groups, and consultants, was used to prepare summaries of the state of knowledge in each area. These summaries are presented in Appendices A, B, and C.

5. Particle-Size Distribution Data

5.1 General Features of Available Data

A major portion (over 95%) of the data currently available on the size of particulates emitted from industrial sources has been obtained by using standard source sampling procedures and the Bahco Micro-Particle Classifier. The Coulter Counter, Whitby centrifuge/MSA Sedimentation, and microscopic techniques have also been used for particle sizing. Cascade impactors, electrostatic precipitators, and thermal precipitators have been used to a limited extent in source sampling, and a small quantity of particle-size data was obtained from investigators using this equipment. A complete list of industrial organizations and research groups that provided particle-size data is given in Appendix D.

In general, the exact source sampling techniques used to obtain the particulates for subsequent sizing have not been defined. In some cases, the thimble size used in the sampling train was indicated. Requests to provide detailed information on this point were made to the groups supplying data, but their general response was that the collection of such information would require an extensive review of their files, and we decided that the time and money required for them to perform such a review were prohibitive for this program. Telephone conversations with knowledgeable individuals in the various organizations did indicate that sampling techniques were "standard".

Particle-size data were found to be extensive for some sources, but rather meager for other sources. Coal-fired power plants, cement kilns, lime kilns, and foundries are in the former category, while sources in the primary and secondary nonferrous metallurgy, iron and steel, and pulp and paper industries fall in the latter category. This nonuniformity in the availability of data made it impossible to provide more than a general indication of the mass of fine particles emitted from some sources.

Another facet of the particle-size distribution data collected during the program is that a significant portion, approximately 85%, was obtained from uncontrolled sources. The lack of particle-size data from controlled sources clearly indicates that neither control equipment manufacturers nor air pollution control agencies have placed any significant emphasis on the particle size of pollutants emitted from control equipment. The main thrust of air pollution control to date has been toward control on a mass basis, with no concern given to the size and number of particles emitted from the control equipment. Failure to collect fine particles constitutes the most severe deficiency of current control equipment because the fine particles emitted contribute significantly to all the major adverse aspects of air pollution (see Appendices B and C).

The lack of particle-size distribution data following control equipment and the lack of measurement of total efficiency where outlet size data are available made it difficult to check calculations of fine-particle emissions. For those sources where adequate particle-size distribution data for controlled sources were available, these outlet distributions were used to check emission calculations performed using size distributions for uncontrolled sources and generalized fractional efficiency curves. Sections 6 and 7 discuss these subjects in more detail.

5.2 Methods of Data Presentation

Particle-size data can be expressed in tabular or graphical form. Presentation of size data in tabular form is more precise as well as more general. Measurements are expressed explicitly in this format. The table can present either particle size *versus* cumulative frequency greater (or less) than specific sizes, or particle-size range *versus* weight or number frequency within the range. The choice between number-size and weight-size is dictated by method of measurement, i.e., whether the data were collected by counting particles or by weighing.

For purposes of illustrating data, there are a number of reasons why representing particle-size distributions graphically is preferable to tabular presentation. One of these is that graphs present the data in such a form that one may learn at a glance something of the deviation of the data, their skewness, and the location of the mode. Another reason is that graphs are much more concise than long tables of measurements. At the same time, they present more complete information than can be indicated by one or two of the usual averages and some measure of the deviation. A third reason for preparing graphs is that they can often be used to obtain numerical values for certain properties of the distribution. Examples are estimates of the arithmetic mean from plots of normally distributed particle sizes, and estimates of the geometric mean from plots of log-normal distributed particle sizes. Still another purpose for plotting particle-size data is to obtain a basis for interpolation or extrapolation of the data. This last reason is quite important for the current study because very few particle-size data are available in the size range of interest (0.01-2 μ).

Several methods are available for graphical depiction of particle size data. Histograms, frequency distribution curves (continuous histogram), and cumulative distribution curves are frequently used to present particle-size data. Figure 1 illustrates a histogram and frequency distribution curve, while Figure 2 presents a cumulative percentage curve. The cumulative percentage curve is suitable for both equidistant and nonequidistant class intervals of particle size. However, the frequency distribution curve is best suited for the graphical presentation of data classified by an equidistant scale. A frequency distribution with a nonequidistant scale, while theoretically possible, would give a distorted picture of the distribution. Such a distortion would necessitate additional inspection of the numerical table of data, and defeat the basic idea of graphical representation. For these reasons, cumulative curves are used extensively in preference to frequency curves.

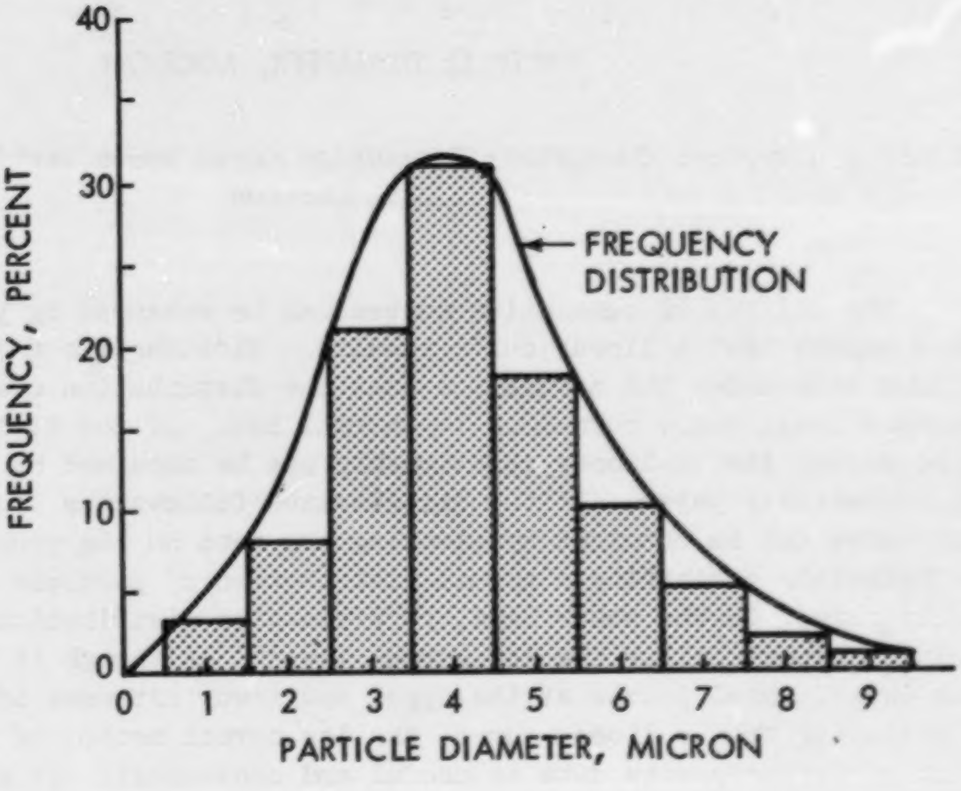

Figure 1 - Histogram Representing a Particle-Size Distribution

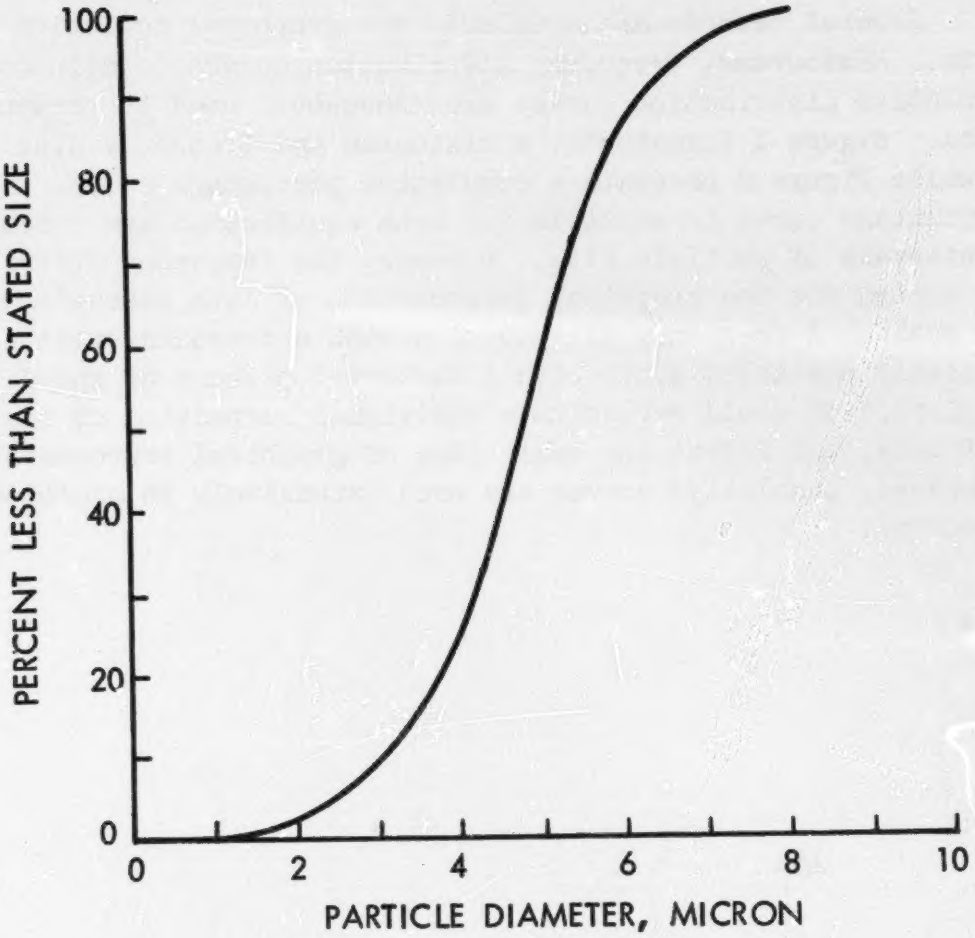

Figure 2 - Typical Cumulative Percentage Curve for a Particle-Size Distribution

The utility of cumulative curves can be enhanced by plotting data in such a manner that a linear curve results. Plotting for a linear curve can be done only under the assumption that the distribution obeys one of the standard laws, e.g., normal or log-normal law. If the distribution obeys the normal law, a linear relationship can be obtained by plotting the data on probability paper. If the distribution follows the log-normal law, a linear curve can be obtained by plotting the data on log probability paper. Materials exhibiting a normal distribution of particle size are relatively rare. On the other hand, particle-size distributions of many particulate systems follow the log-normal law.[16] Although it is common to find the experimental points at the upper and lower extremes of the distribution deviating from a linear curve, the log normal method of plotting and representing particle-size data is useful and convenient. It also permits interpolation between points as well as limited extrapolation beyond the experimental range covered. Figure 3 shows a cumulative curve for a fly ash, and Figure 4 presents the same data on log probability coordinates.

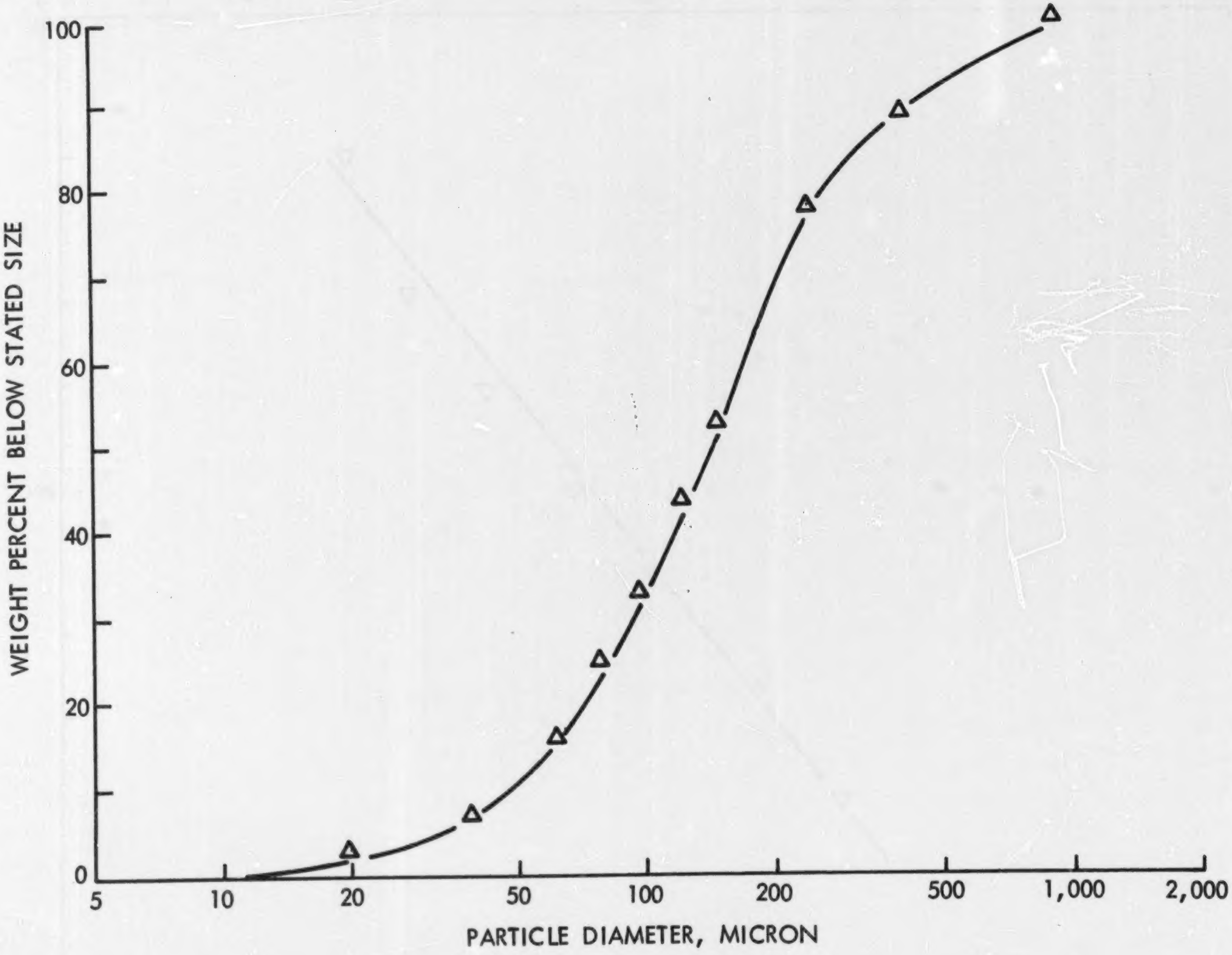

Figure 3 - Cumulative Percentage Curve for Particle Size Distribution of Fly Ash

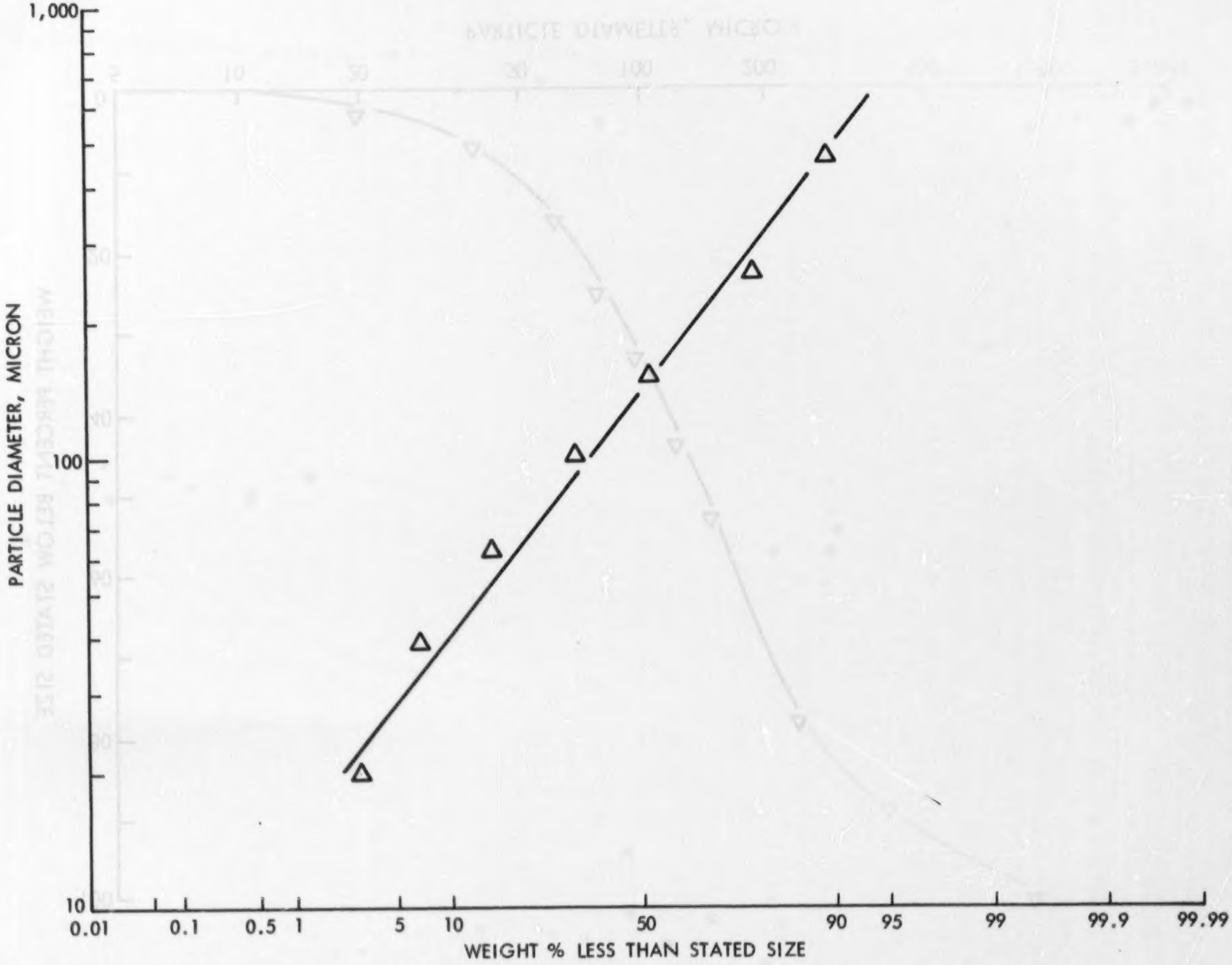

Figure 4 - Log Normal Curve for Fly Ash Particle-Size Distribution

As noted in Section 5.1, nearly all the particle-size data available for use in estimating fine-particle emissions were obtained by using the Bahco Micro-Particle Classifier. The lower range of applicable particle diameter for the Bahco instrument is generally quoted as 1-5 μ (Appendix A, Section 3.1-1). Since the particle size range of interest to the program is 0.01-2 μ, it was necessary to select a method of data presentation that would facilitate extrapolation of the particle-size data.

Extrapolation would clearly be enhanced by using a presentation method that resulted in a linear curve. Consideration of the plus and minus aspects of the available graphical methods indicated that the log-normal distribution was the best method available. The basic limitations of the method have not been ignored in its selection, but there does not appear to be any better method of presentation that will facilitate the extrapolation. Also, the log-normal distribution was found to be useful in representing fractional efficiency curves for control devices (see Section 6).

Although available particle-size data were obtained primarily by the Bahco method, attempts were made to compare size distributions by various measuring techniques whenever possible. Particle-size distributions of particulates emitted from coal-fired power plants have been measured by several methods. Figure 5 illustrates a comparison of size distributions obtained by Coulter Counter, optical methods (regular and electron microscope), and the Bahco classifier. The Coulter Counter data represent the arithmetic mean of 18 individual analyses, while the optical data are the arithmetic mean of 10 individual analyses. The arithmetic curve for the Bahco data was obtained from over 300 individual analyses. Since the stack sampling techniques used to obtain the samples for subsequent sizing are not known in detail, only very general comments will be given on the differences in the size distributions. The differences in the Coulter Counter and Bahco distributions may be a result of the fact that the Bahco classifier subjects the ash to much higher attrition than the Coulter Counter, and probably breaks up most of the agglomerates. The electron microscope is a more exact method of sizing particles, especially in the smaller size range. The increase in percentage of smaller particles shown by the optical data is explainable in terms of the differences among the different methods.

Figure 6 illustrates the variation in particle-size distribution that can result from the use of different source sampling devices. Particle-size data are shown for the effluent from a kraft pulp mill recovery furnace. The data were obtained by using a stainless steel cascade impactor,[2] capable of in-stack sampling, and a small electrostatic precipitator (optical sizing).[3] No specific comments can be made about the difference in size distributions because only a limited number of samples were taken from two separate furnaces, and the operating characteristics of the furnaces are not defined in sufficient detail.

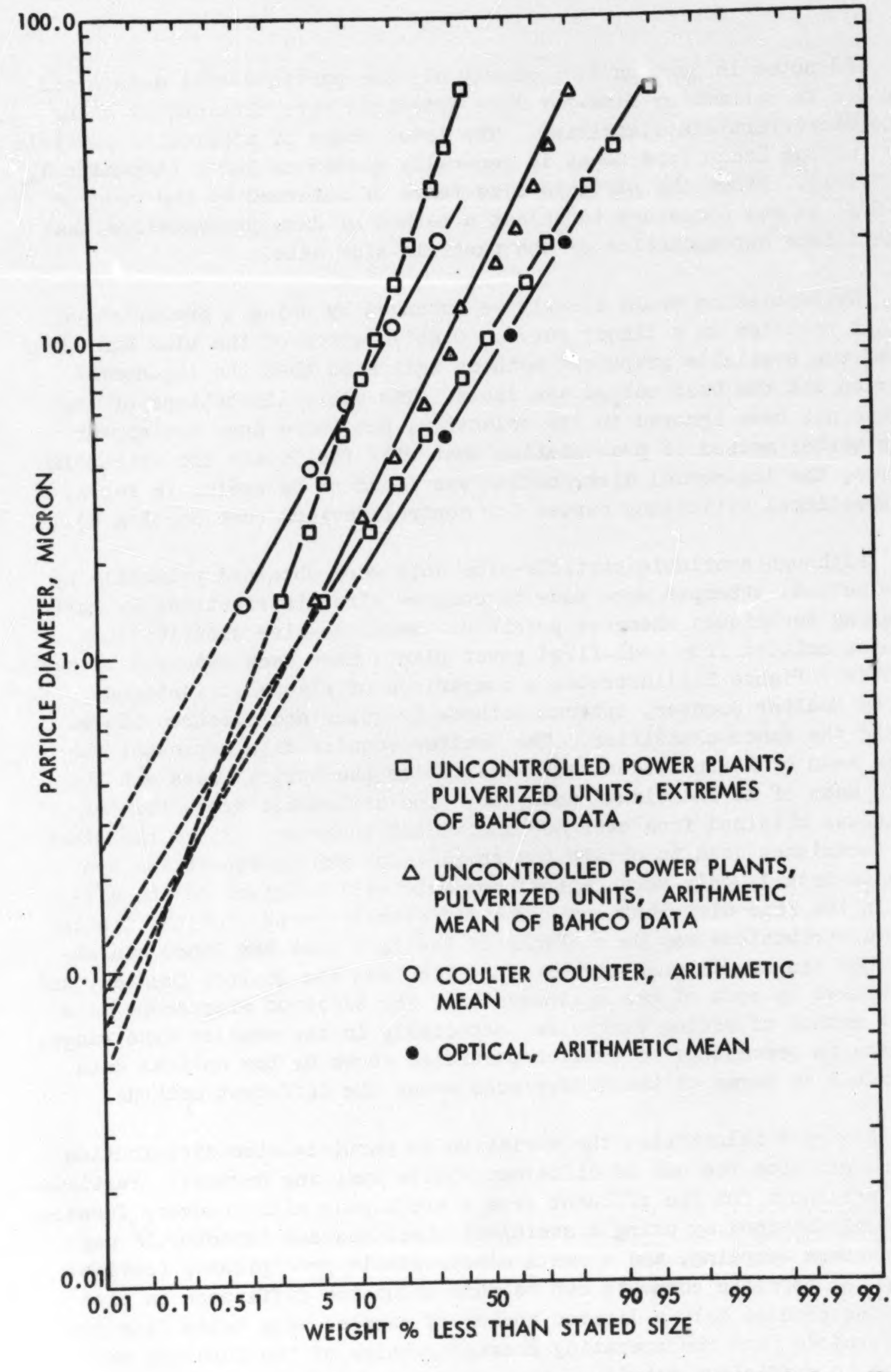

Figure 5 - Particle-Size Distributions of Particulates Emitted from Uncontrolled Power Plants (pulverized coal-fired boilers)

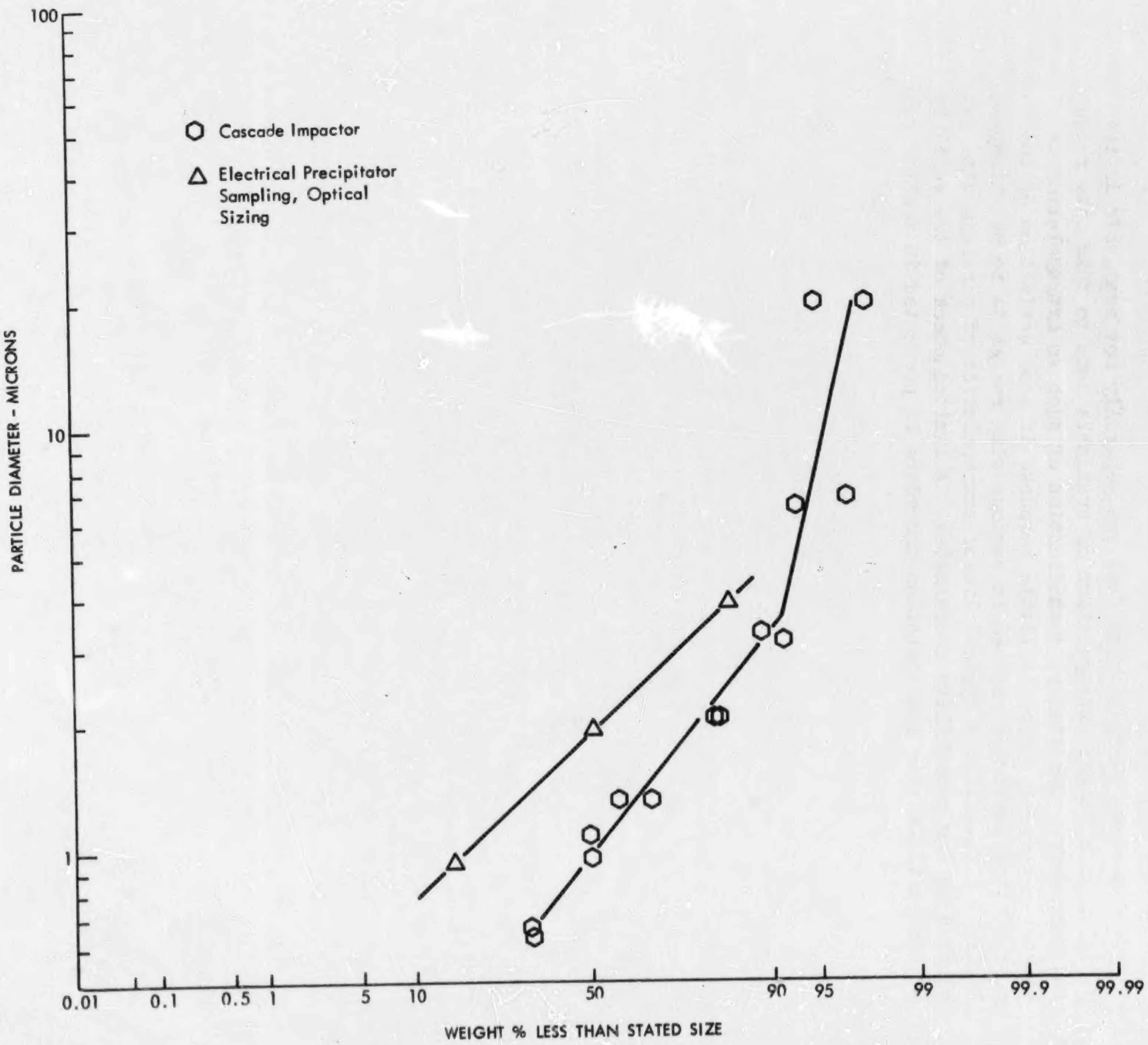

Figure 6 - Particle-Size Distribution of Particulates Emitted from Uncontrolled Recovery Furnace, Kraft Pulp Mill

Because particle-size data are generally not available in the 0.01-2 μ size range, extrapolation of available data to this size range was necessary. Admittedly, justification of such an extrapolation is tenuous. However, there is little recourse if some estimation of the mass of fine particles emitted in various size ranges is to be attempted. Figure 7 illustrates a typical linear extrapolation of particle-size data plotted on log probability coordinates. A limited check of the validity of the particle size extrapolation procedure is presented in Section 7.1.

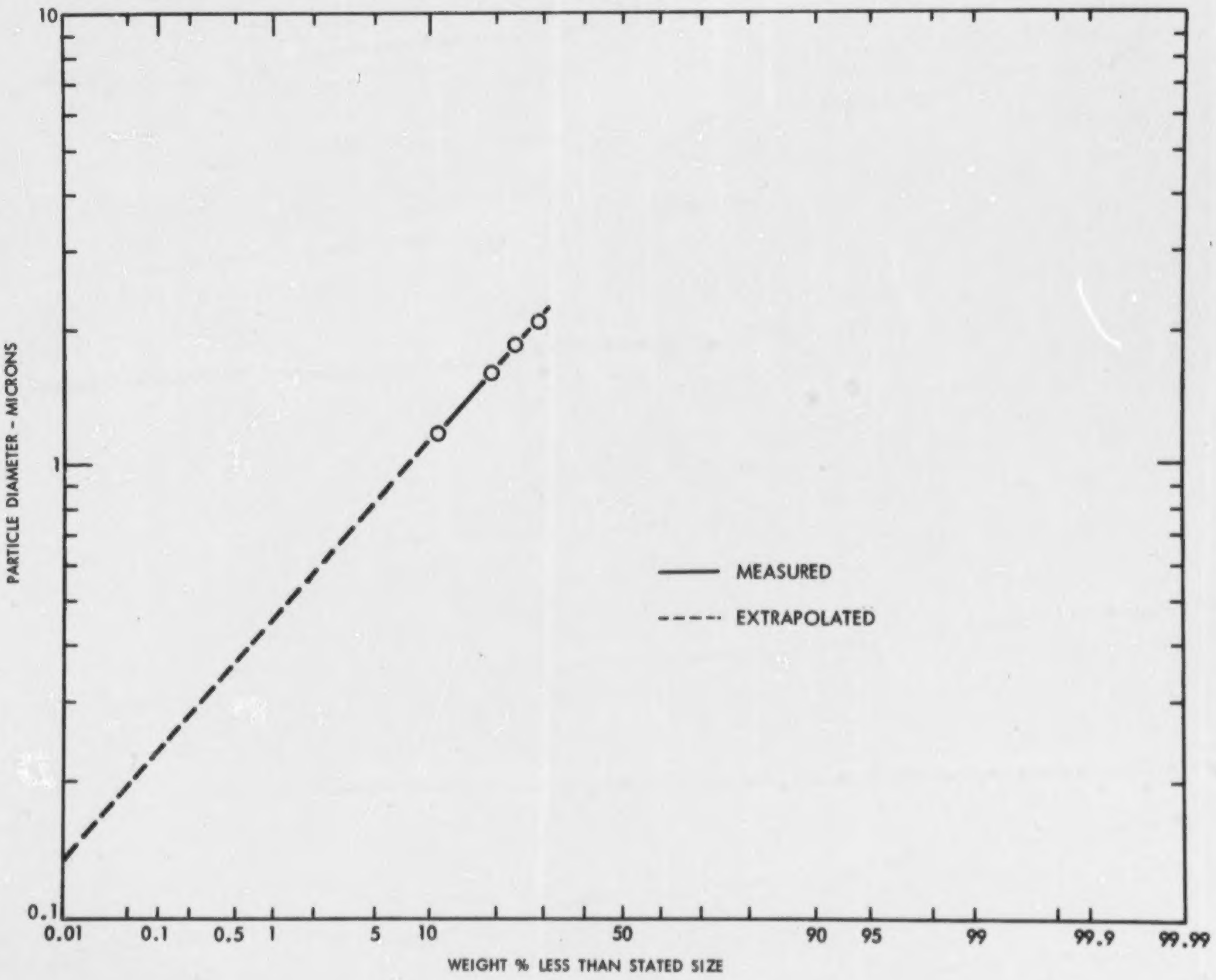

Figure 7 - Extrapolated Particle-Size Distribution of Particulates Emitted from Cement Kiln Controlled by Electrostatic Precipitator

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6. Fractional Efficiency of Control Equipment

Calculation of the quantity of fine particulate emitted from controlled sources requires information relating to the collection efficiency of control equipment for each particle size or size range. Graphs depicting this relationship are commonly referred to as "fractional efficiency curves." During the program, available data on fractional efficiency characteristics of control equipment were collected and reviewed. The pertinent aspects of this activity are discussed in the following sections.

6.1 Acquisition and Review of Data

Using the library of articles and reports collected for the Particulate Pollutant System Study, all of those related to control equipment were scanned to retrieve any that contained information on fractional efficiency. Special attention was paid to those containing data for particle sizes below 5 μ.

Our retrieval of fractional efficiency information revealed that limited data are available, and that the reliability of much which are available is hampered by lack of specifics pertaining to sampling and analysis techniques and operating conditions. Many of the data were determined for pilot scale units, and tests were most often conducted using specific test dusts or monodisperse aerosols. In many cases the published curves were only identified as "typical" for a certain type device with no other information or references.

Many of the available fractional efficiency curves are plotted on linear coordinate paper and do not have sufficient detail to be useful in the fine-particle range (0.01-2 μ). This was expected since the more common sampling and analysis techniques are not accurate much below 5 μ. Also, until recently there has been limited interest or need to give much consideration to the particles below 5 μ as they relate to overall efficiency of control equipment.

Many of the curves published in the literature are those originated by Stairmand.4/ The fractional efficiency curves prepared by Stairmand refer to particles of density 2.7 g/cm^3 and are, in most cases, the result of prolonged tests on full-size plants.4/ It is assumed that sedimentation apparatus was used to carry out the particle-size analysis.6/

The review of available fractional efficiency curves indicated that a statement of the overall efficiency of the device is often not included on the graph or in the text. Overall efficiency could not be reported for those units tested using monodisperse aerosols, but it could

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be reported when other methods were used or where in-plant tests were conducted.

In some cases the overall efficiency of the device has been included with the fractional efficiency curve, but some discrepancies were noted. For instance, the overall efficiency was 99.5%, whereas the fractional efficiency curve never exceeded 95%. This relationship, of course, is an impossibility which raises doubt as to the validity of the information.

The fractional efficiency data for each type of control device varied over a wide range since the overall efficiency and design of these devices vary over a wide range. However, the shape of the fractional efficiency curves was similar for each type of device except for fabric filters. Peterson and Whitby reported that the fractional efficiency of a fabric collector goes through a minimum at about 0.3 μ with increasing efficiency above and below 0.3 μ.7/ Their conclusion was based on fractional efficiency measurements using monodisperse aerosols. However, such results may not be applicable to industrial fabric filters and reverse-jet filters, and the efficiency of these devices does not depend on particle size.8,9/

Recent data taken on a felt bag fabric filter using a cascade impactor shows minimum efficiency (about 96%) occurring at 0.1-0.2 μ but there is no indication of increasing efficiency when the particle size decreases to 0.1 μ.10/ More experimental data will be necessary to resolve the fractional-efficiency characteristics of industrial fabric filters in the fine-particle range.

6.2 Data Analysis

Available fractional efficiency data apply to specific industry sources in only a few cases. Therefore, the data were separated on the basis of control devices (i.e., cyclones, electrostatic precipitators, wet scrubbers, and fabric filters). The fractional-efficiency data for each control device category were plotted on log-probability paper to magnify the efficiency relationship for the smaller particles and to assess the possibility of extrapolation down to 0.01 μ. Log probability coordinates were chosen on the basis that a linear relationship had been previously reported by other investigators.7,11,12/ Reference 13 indicates that a linear correlation can also be obtained for certain types of cyclones by using semi-log coordinates. Notation of all available information relating to specific type of device, overall efficiency, operating conditions (such as pressure drop or water rate, etc.), and sampling and analysis techniques were included on the log probability plots.

Figure 8 illustrates data for electrostatic precipitators, while Figure 9 presents fabric filter fractional efficiency. Wet scrubber characteristics are given in Figures 10 and 11. Fractional efficiency characteristics of cyclones are presented in Figures 12 to 16.

Symbol Identification for Figure 8

□ Stairmand, Dry ESP[4]

● Stairmand, Irrigated ESP[4]

◆ Well Conditioned Dust, Particle Sizing by Electron Microscope[25]

✖ Wet ESP, High Resistivity Dust, Particle Sizing by Electron Microscope[25]

○ No Information Except 99.9 % Efficient[22]

⊗ No Information Except 99.9 % Efficient[23]

▼ Pilot Scale ESP on Coal-Fired Boiler; Gas Velocity 2.62 Ft/Sec

△ "Typical" Curve[27]

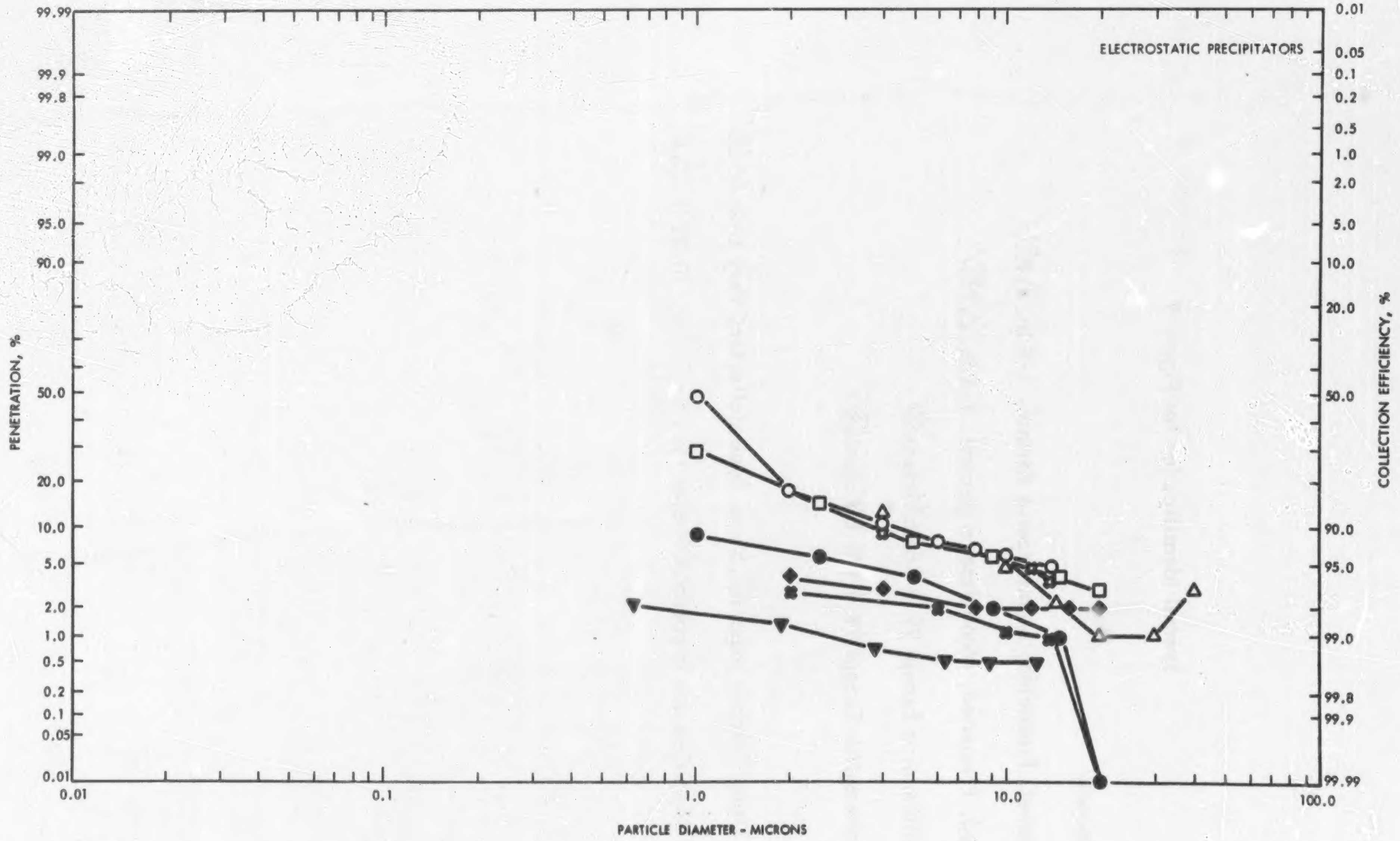

Figure 8 - Fractional Efficiency Data for Electrostatic Precipitators

Symbol Identification for Figure 9

○ Stairmand[4]

△ 35 Shakes, Precoated, Monodisperse Aerosol, 1-4 In. △P[21]

▲ Loaded, Precoated, Monodisperse Aerosol, 1-4 In. △P[21]

✖ No Information Except 99.9 + % Efficient[22]

✕ No Information Except 99.9 + % Efficient[23]

□ 24/

● Data Using Cascade Impactor, Shake Type Collector, Very Low △P[10]

◇ Data Using Cascade Impactor, Ultrajet Type Collector, 10-12 In. △P

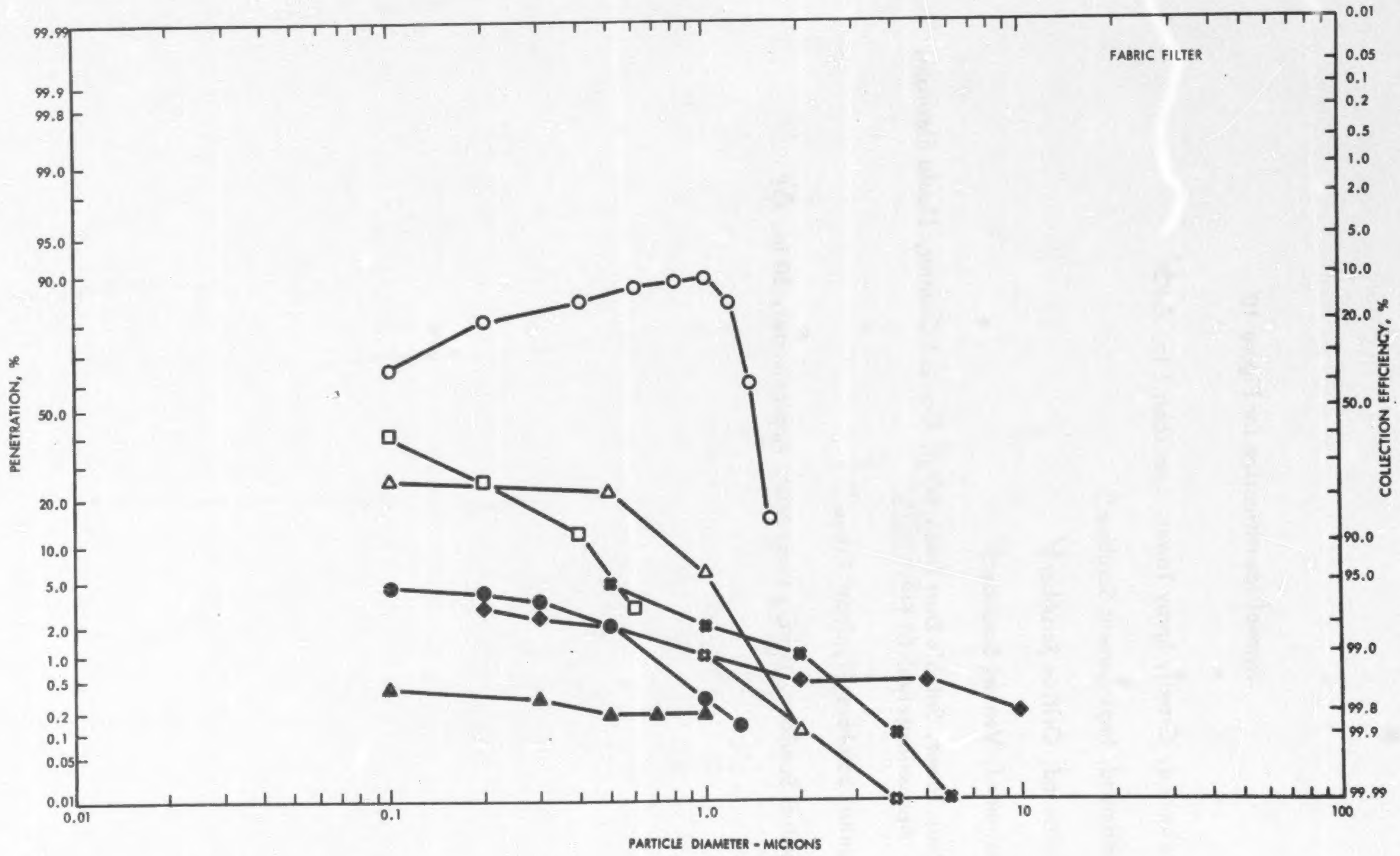

Figure 9 - Fractional Efficiency Data for Fabric Filters

Symbol Identification for Figure 10

△ Stairmand, Gravity Spray Tower, Less Than 1 In. ΔP[4]

✖ Stairmand, Impingement Scrubber[4]

◆ Stairmand, Orifice Scrubber[4]

▼ Stairmand, Venturi Scrubber[4]

● Spray Tower, Soluble Dust (Na_2, SO_4), Optical Counter, Liquid Flowrates Approximately 0.03 Ft^3/Min[28]

☐ Venturi Scrubber "Typical" Curve[29]

⊗ Venturi Scrubber, H_3PO_4 Plant Mist, Approximately 30 In. ΔP

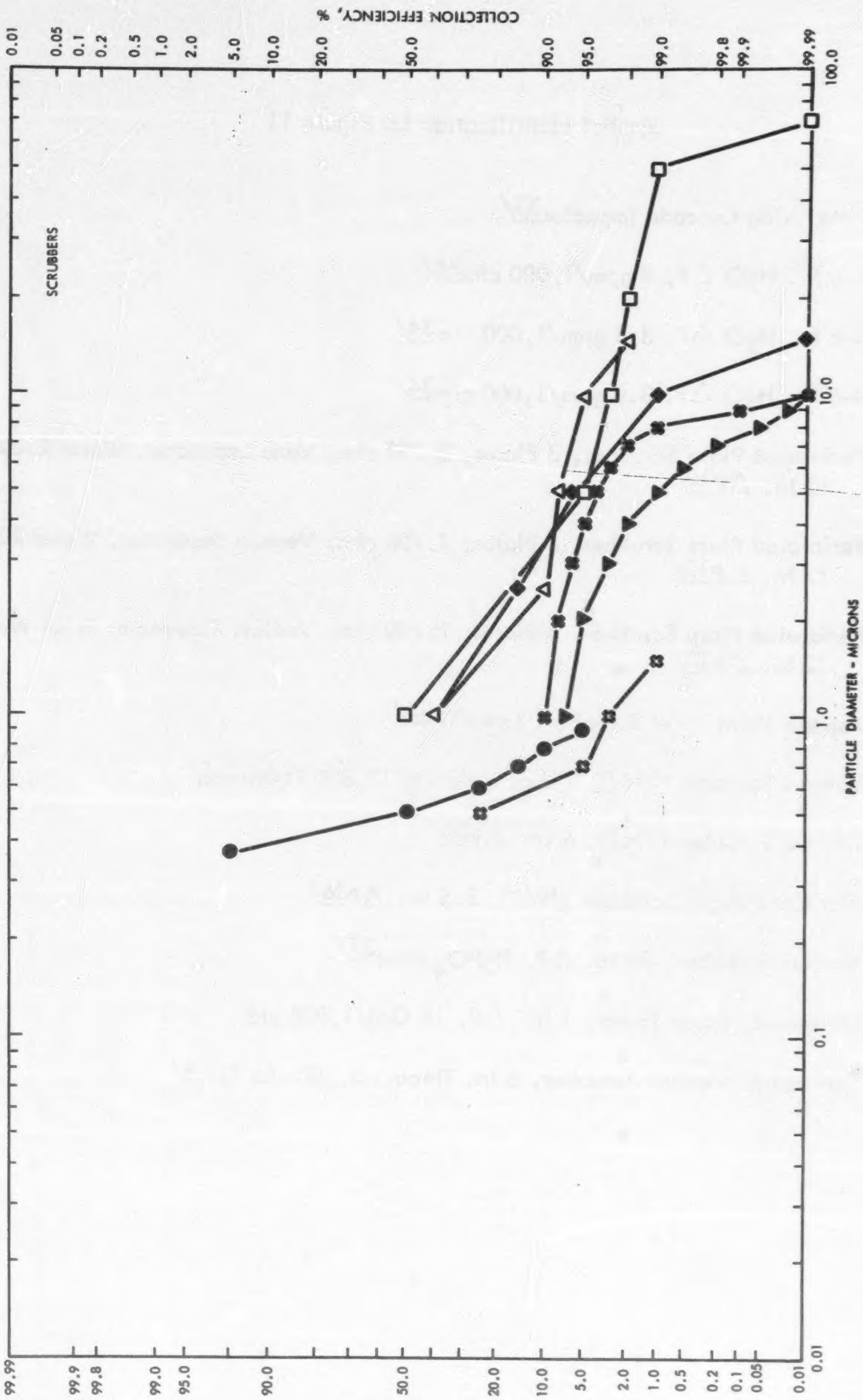

Figure 10 - Fractional Efficiency Data for Wet Scrubbers

Symbol Identification for Figure 11

□ Data Using Cascade Impactor[33]

◗ 4-6 In. H_2O ΔP, 4 gpm/1,000 cfm[34]

∩ 4-6 In. H_2O ΔP, 3.3 gpm/1,000 cfm[34]

✡ 4-6 In. H_2O ΔP, 3.0 gpm/1,000 cfm[34]

✣ Perforated Plate Scrubber, 3 Plates, 2,750 cfm, Vane Separator, Water Recycled, 12 In. ΔP[10]

● Perforated Plate Scrubber, 3 Plates, 2,750 cfm, Venturi Separator, Water Recycled, 12 In. ΔP[10]

▼ Perforated Plate Scrubber, 3 Plates, 2,750 cfm, Venturi Separator, Fresh Water, 12 In. ΔP[10]

✤ Asphalt Plant, Wet Scrubber, Low ΔP[35]

▱ Venturi Scrubber (1967), Throat Velocity 17,800 Ft/Min[36]

◆ Orifice Scrubber (1967), 6 In. ΔP[36]

○ Wet Centrifugal Scrubber (1967), 3.5 In. ΔP[36]

⬡ Venturi Scrubber, 30 In. ΔP, H_3PO_4 Mist[37]

△ Stairmand, Spray Tower, 1 In. ΔP, 18 Gal/1,000 cf[4]

⌂ Stairmand, Venturi Scrubber, 6 In. Throat, 3,500 cfm Gas[4]

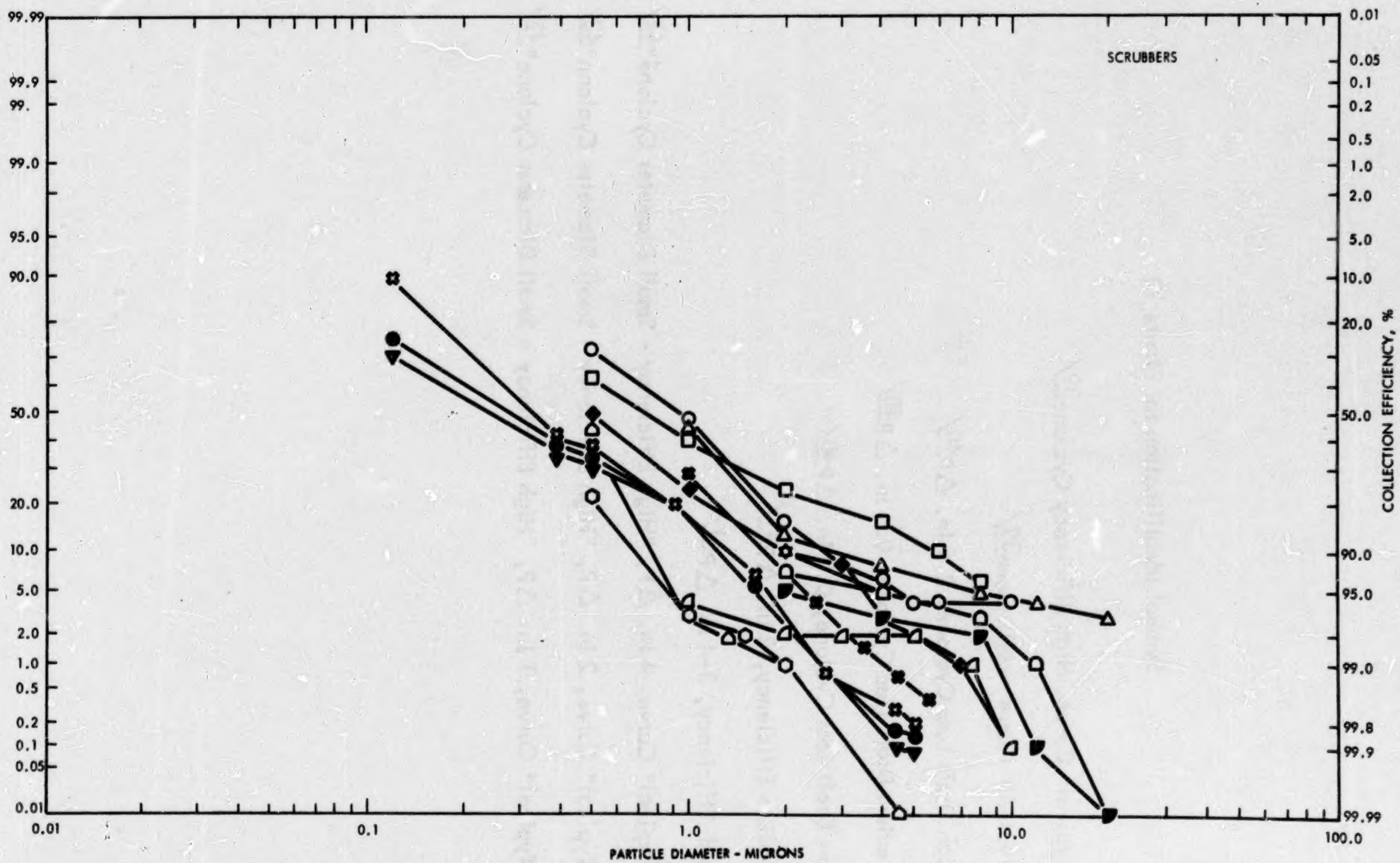

Figure 11 - Fractional Efficiency Data for Wet Scrubbers

Symbol Identification for Figure 12

⏢ "Typical" Curve, High Efficiency Cyclone[39]

△ "Typical" Curve, Multiclone[39]

⬠ High Draft Loss Cyclone, 2.5 In. ΔP[40]

⌘ Medium Draft Loss Cyclone, 0.4 In. ΔP[40]

○ Low Draft Loss Cyclone, 0.2 In. ΔP[40]

◆ Medium Efficiency, 2 In. ΔP[41]

□ High Efficiency, 3-4 In. ΔP[41]

✖ "Typical" Curve, 4 In. ΔP, "High Efficiency - Small Diameter Cyclone"[42]

● "Typical" Curve, 2 In. ΔP, "High Efficiency - Small Diameter Cyclone"[42]

▼ "Typical" Curve, 1 In. ΔP, "High Efficiency - Small Diameter Cyclone"[42]

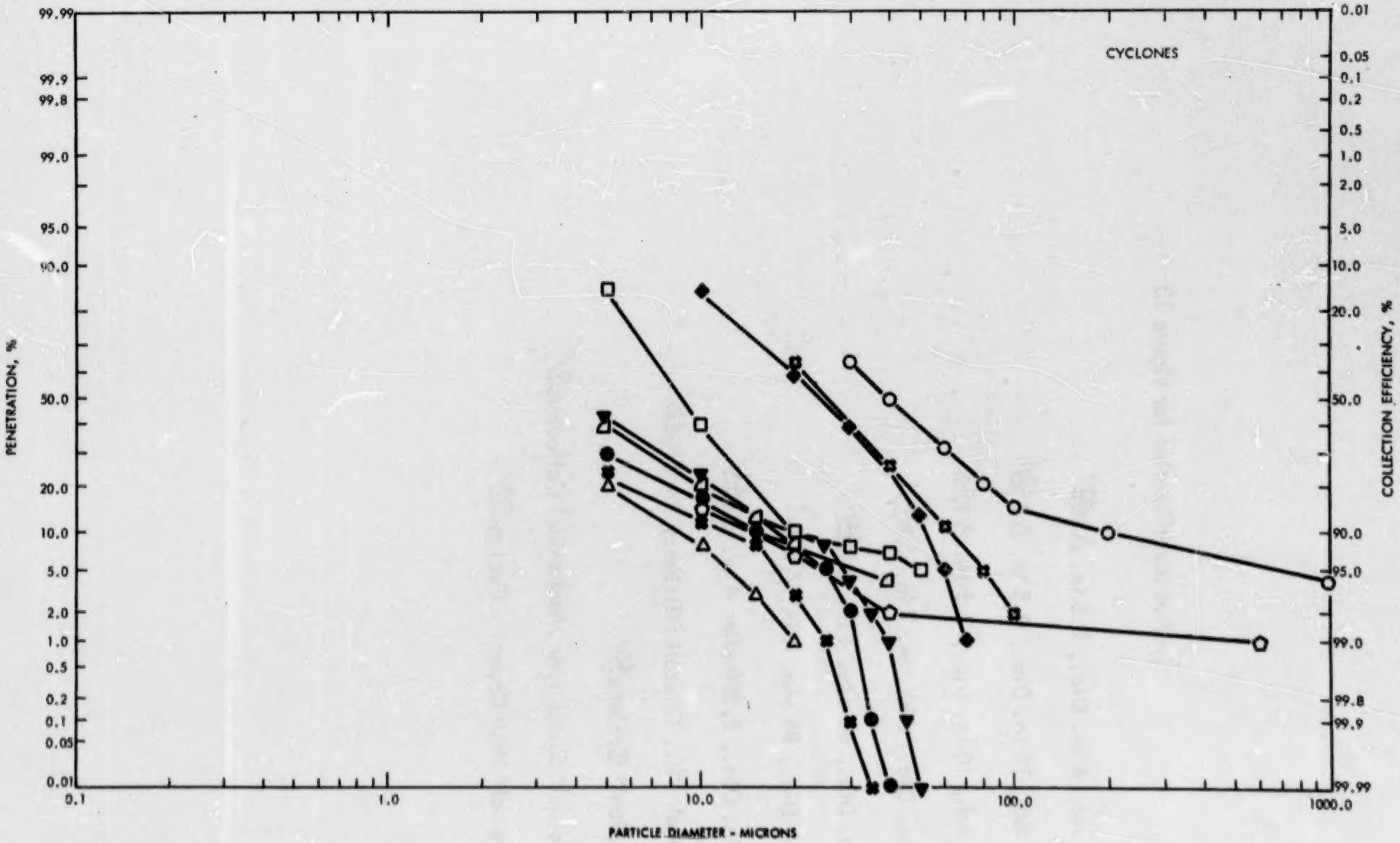

Figure 12 - Fractional Efficiency Data for Cyclones

Symbol Identification for Figure 13

⌂	Fly Ash, 6 In. Dia., 2.5 In. Δ P[43]
⬠	Fly Ash, 10 In. Dia., 2.5 In. Δ P[43]
◢	Fly Ash, 10 In. Dia., 2.5 In. Δ P[43]
□	12 In. Dia., 610 cfm, 7 In. Δ P[44]
✖	5 In. Dia., 65 cfm, 4 In. Δ P[44]
●	5 In. Dia., 85 cfm, 4 In. Δ P[44]
△	20 In. Dia., 2,500 cfm, 4 In. Δ P[44]
✕	Asphalt Plt., Overall Efficiency 94.7 %[45]
▼	"Typical" Cyclone[46]
○	"Typical" Scroll Type Mechanical Collector[39]
◆	"Typical" High Capacity Cyclone[39]

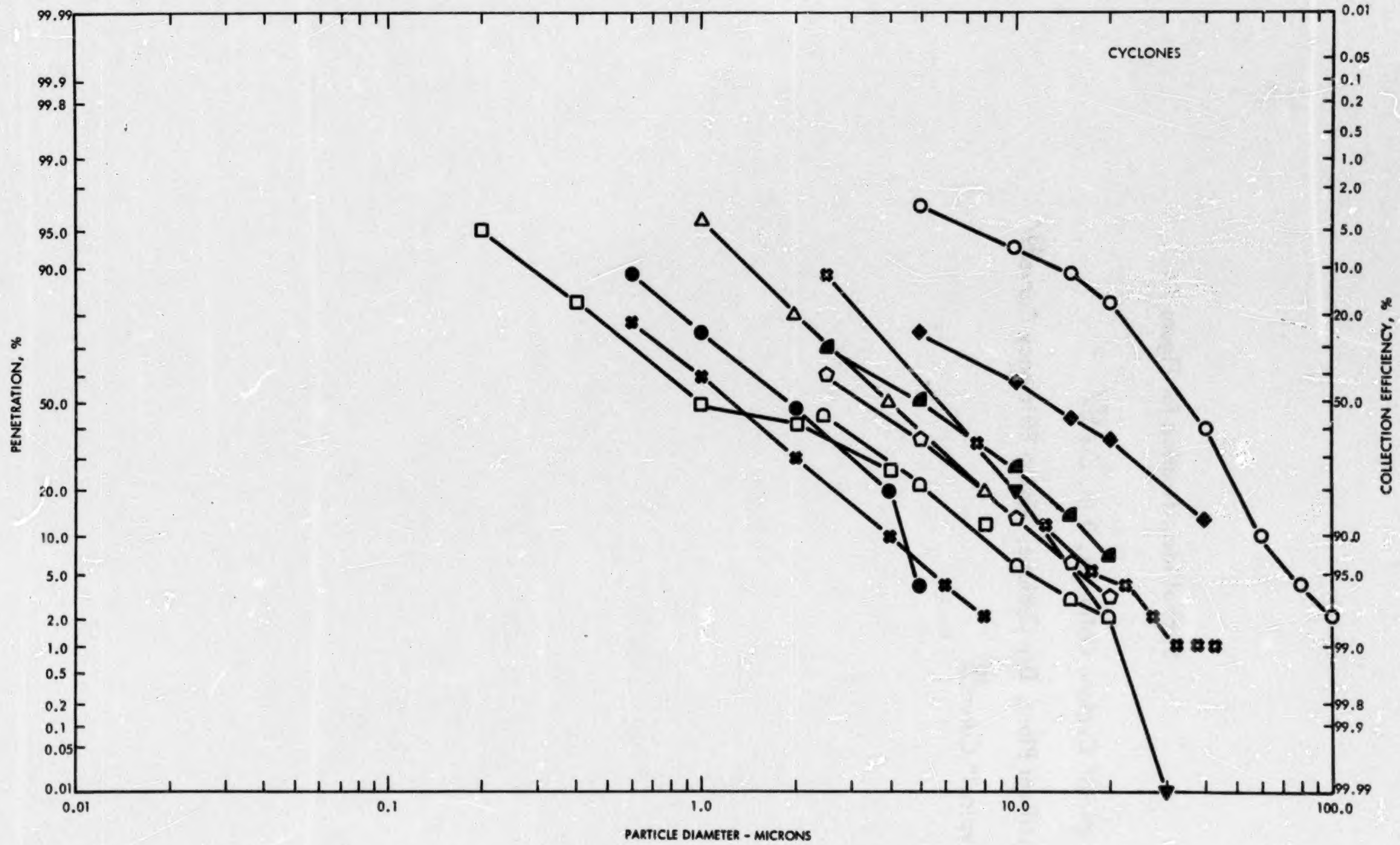

Figure 13 - Fractional Efficiency Data for Cyclones

Symbol Identification for Figure 14

□ "Typical" Cyclone Collector, 3 In. ΔP[47]

▼ Fertilizer Plant, Dry Cyclone, Design Efficiency Curve[48]

○ "Typical" Curve[49]

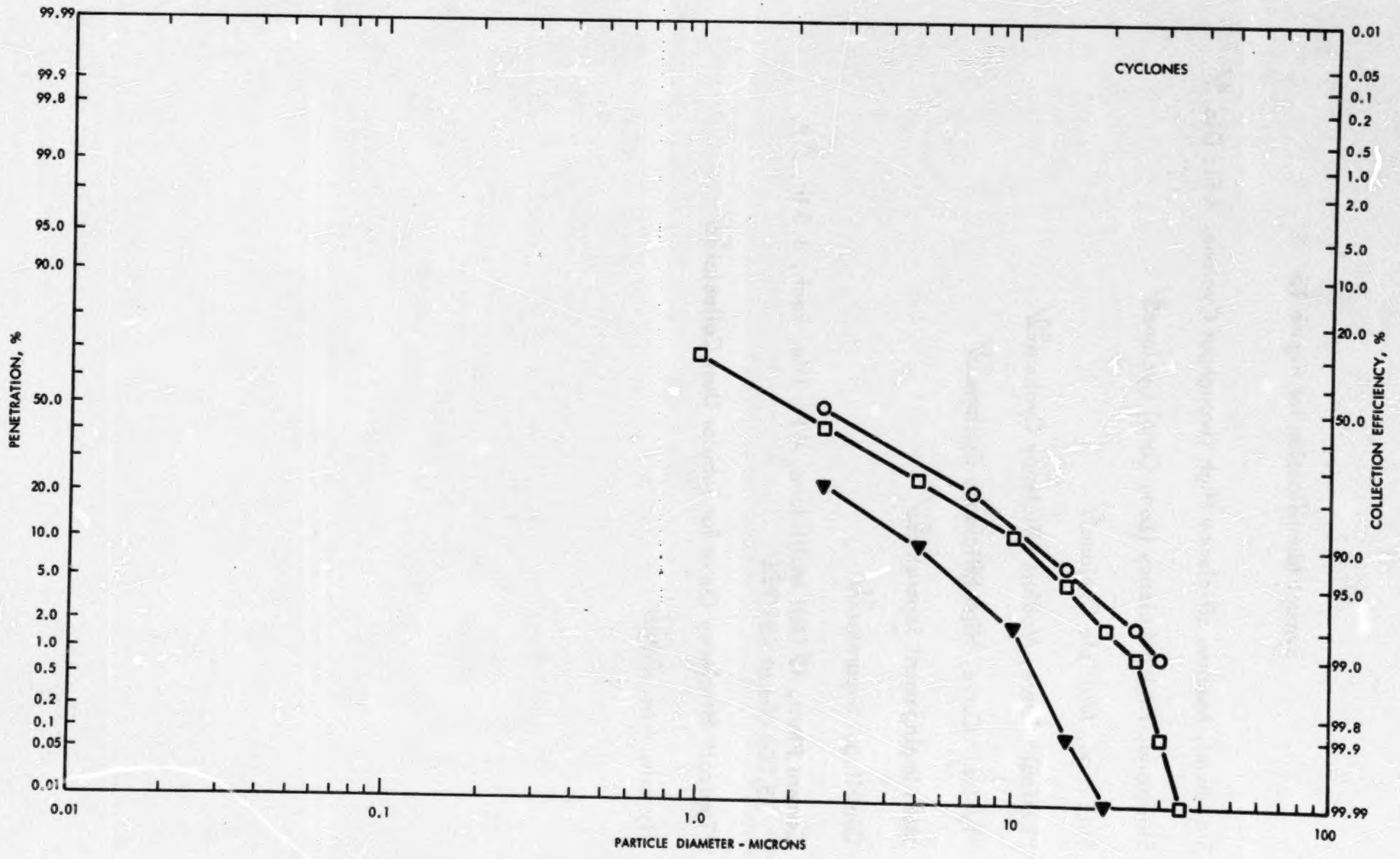

Figure 14 - Fractional Efficiency Data for Cyclones

Symbol Identification for Figure 15

✖ Stairmand, Medium Efficiency High Throughput Cyclone, 4 Ft. Dia.[4]

□ Stairmand, High Efficiency (Long Cone) Cyclone[4]

△ Stairmand, Multiple Cyclone[4]

○ "Typical" Curve, Medium Efficiency Cyclone[50]

◺ "Typical" Curve, High Efficiency Cyclone[50]

◆ Mesh Impingement Separator[51]

⬠ Centrifugal Separator[51]

▼ Cement Plant, 12 Unit Multiclone, 4 Ft. Dia. Each, 3.5 In. ΔP, 75,000 cfm at 450°F[52]

● "Typical" Efficiency Curve for Tubular Dust Collector[53]

⌘ Fly Ash, 4 In. ΔP[54]

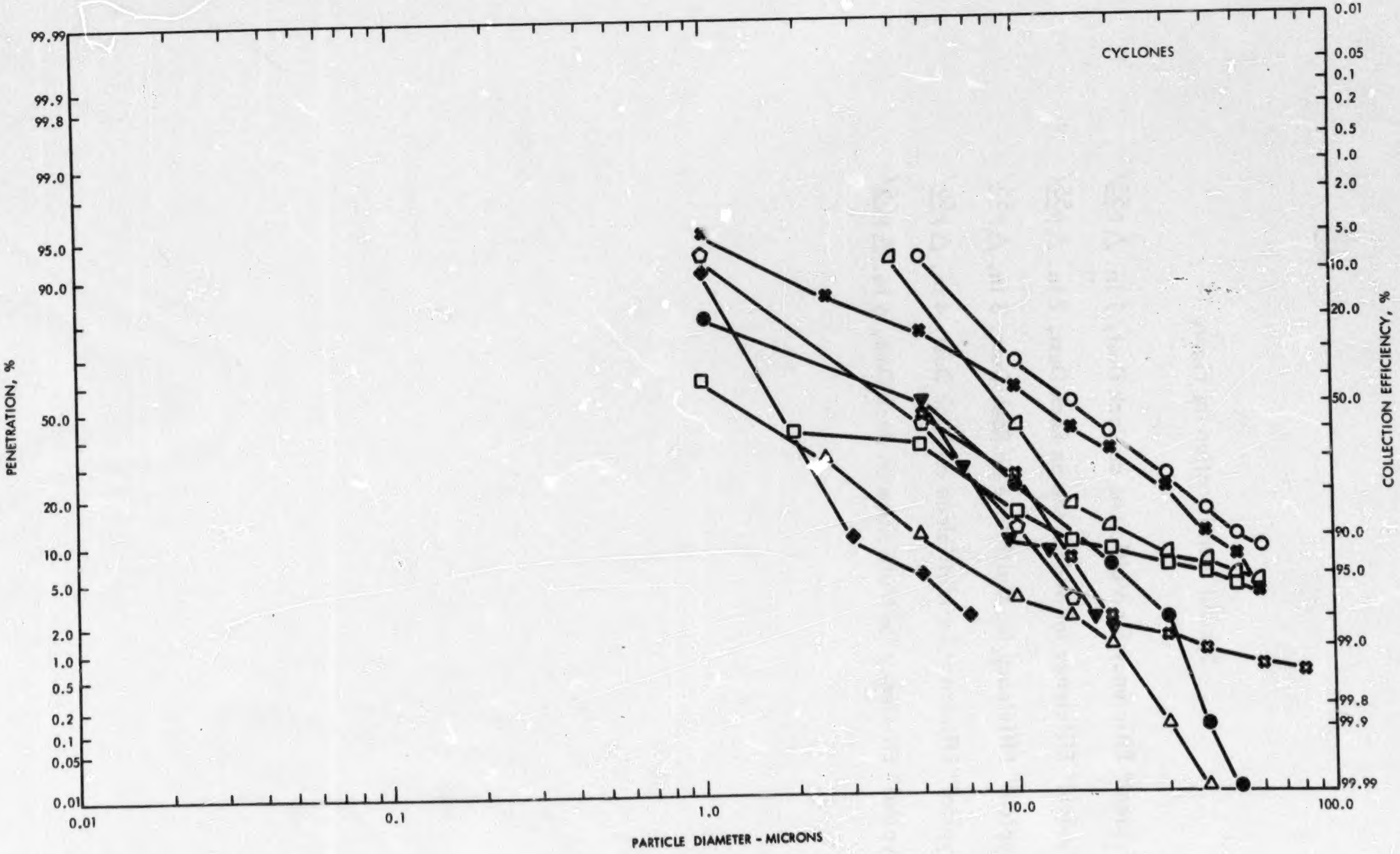

Figure 15 - Fractional Efficiency Data for Cyclones

Symbol Identification for Figure 16

○ "Typical" Efficiency for Multiclone on Rock Dust, 1 In. ΔP[55]

◆ "Typical" Efficiency for Multiclone on Rock Dust, 2 In. ΔP[55]

△ "Typical" Efficiency for Multiclone on Rock Dust, 3 In. ΔP[55]

✖ "Typical" Efficiency for Multiclone on Rock Dust, 4 In. ΔP[55]

□ "Typical" Efficiency for Multiclone on Rock Dust, 6 In. ΔP[55]

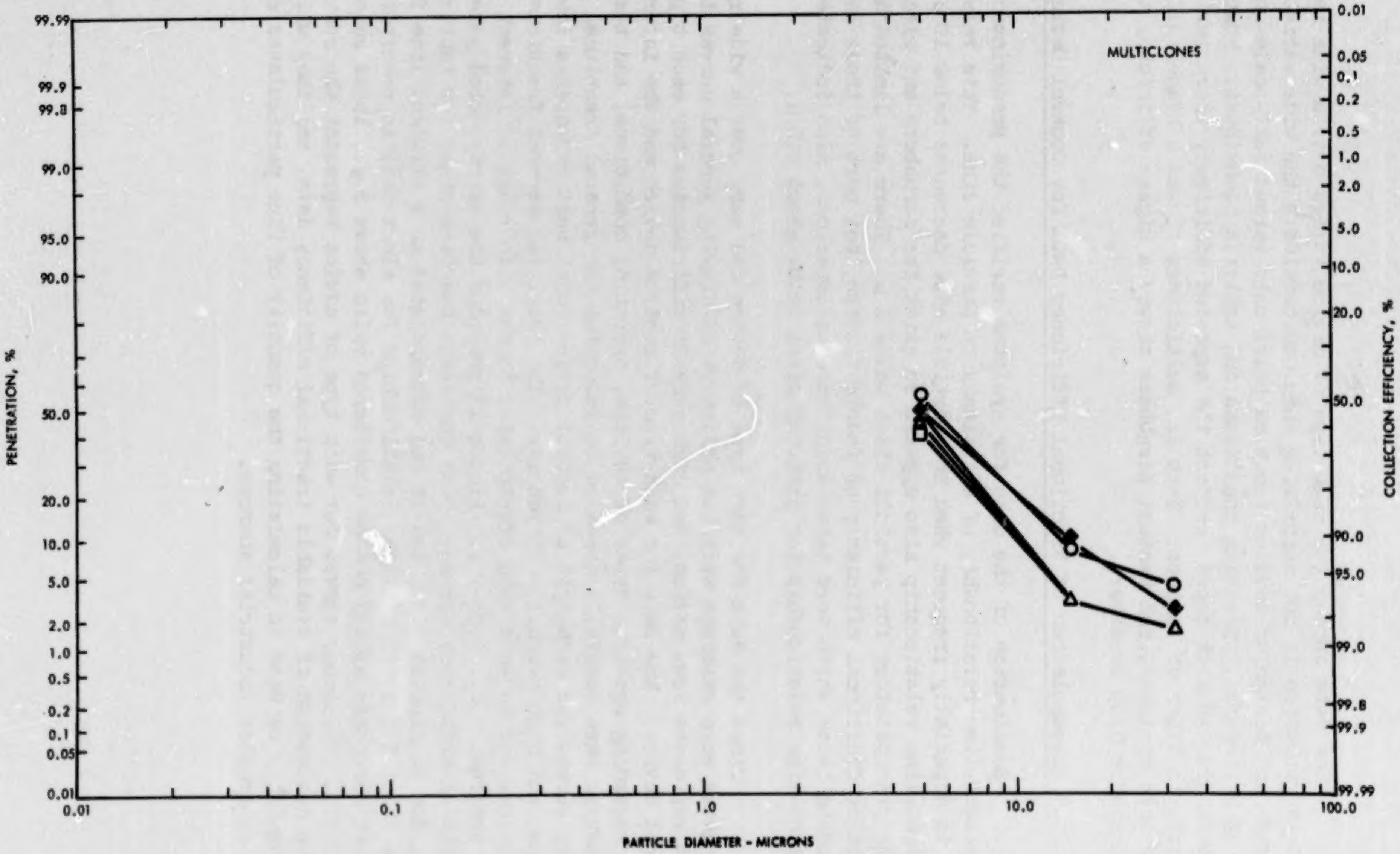

Figure 16 - Fractional Efficiency Data for Cyclones

The data spread for each type of device varied over a wide range, but this variation is not surprising when one considers the wide variation in types and design of devices (such as pilot unit versus full-scale unit), testing procedures, operating conditions and analysis techniques. However, the data did, in most cases, reflect the expected efficiency characteristics of specific types of devices. That is, multiclones showed a higher efficiency curve than cyclones, and Venturi scrubbers showed a higher efficiency than low pressure drop scrubbers.

6.3 Extrapolation of Fractional Efficiency Data for Control Devices

Examination of the data for cyclones verified the predominance of a straight-line relationship of efficiency to particle size. This relationship is especially frequent when the particle size decreases below 10 μ. A straight-line relationship also appears to exist for scrubbers and electrostatic precipitators for particle sizes below 3 μ. There are limited data regarding fractional efficiency of fabric filters, but part of these data, including those which were taken using cascade impactors, also indicate a straight-line relationship for particle sizes below about 0.5 μ.

Since the data for each type of device did vary over a wide range, the curves were examined with the objective of drawing general curves that would represent low, medium, and high overall efficiencies for each type of control device. The data for each type of control device and the information regarding specific types of devices, operating conditions, and testing procedures were carefully assessed to determine the general fractional efficiency curves for each type of control device which best represents low, medium, and high overall efficiencies. The resulting general fractional efficiency curves were then extrapolated to the size range of interest to this program, i.e., 0.01-2 μ. Figure 17 presents the extrapolated general fractional efficiency curves. Only one curve has been drawn for fabric filters, due to limited data, and it was extrapolated as a straight line from below about 0.5 μ. The linear relationships for electrostatic precipitators and wet scrubbers should not be considered valid above 3 μ. These general fractional efficiency curves for each type of device represent the results of the evaluation of available fractional efficiency data, and they will subsequently be used in calculating the quantity of fine particulates emitted from controlled industrial sources.

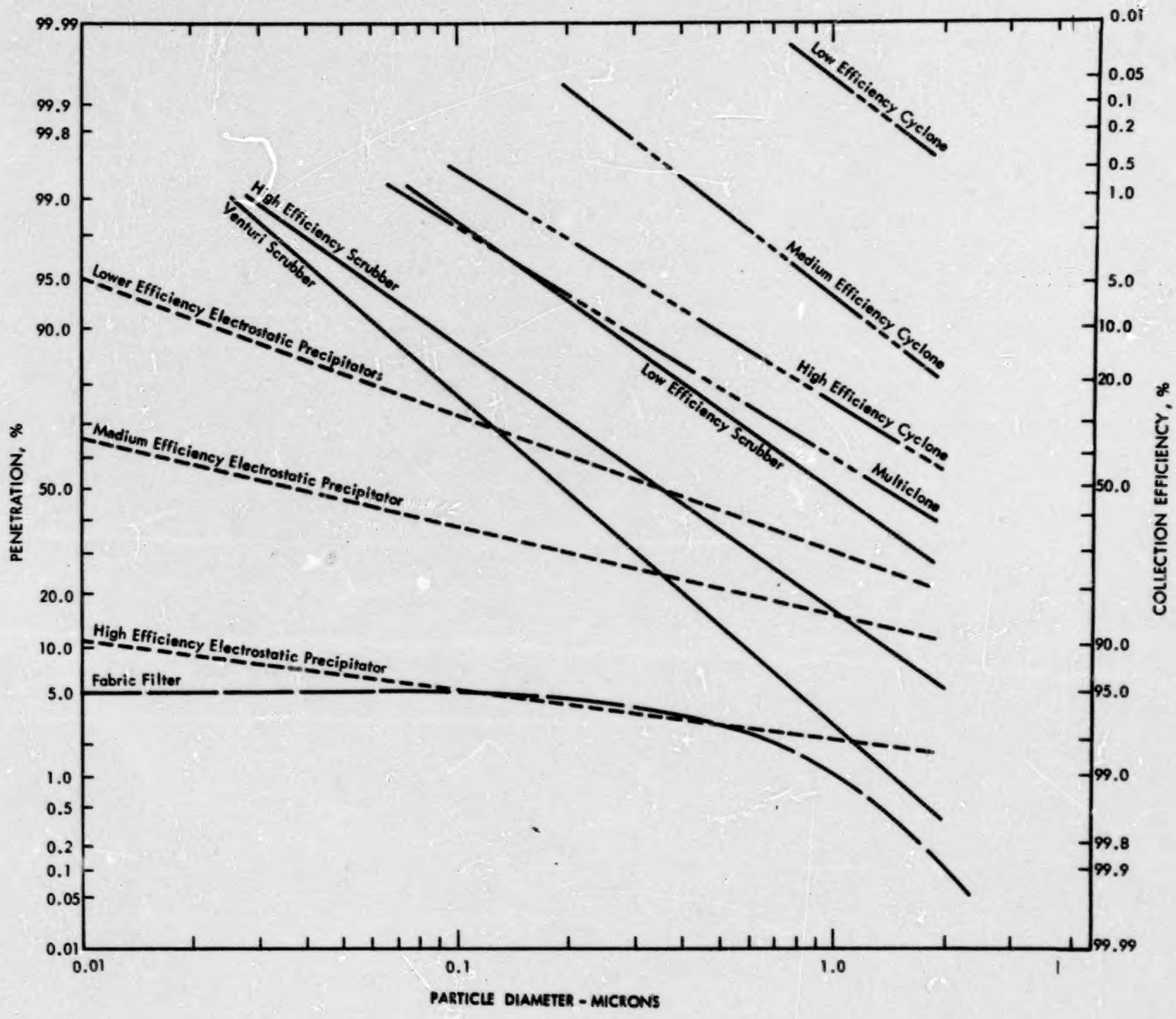

Figure 17 - Extrapolated Fractional Efficiency of Control Devices

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7. Current Level of Fine Particulate Emissions (1969-1970)

The procedure used to calculate the current level (1969-1970) of fine particulate emissions is similar to that used in calculating total mass emissions.[1] The same 1968 production figures and emission factors are used. However, to calculate quantities emitted within given size ranges, it is necessary to have the following additional information:

a. Particle-size distribution for particulates emitted by the uncontrolled source (measured or extrapolated).

b. Percent application of control, with a breakdown of this percent application of control into the percent application of each type of control device (i.e., cyclones, scrubbers, electrostatic precipitators, and fabric filters).

c. Fractional efficiency characteristics of each of these control devices (measured or extrapolated).

Since, in general, particle-size distributions from uncontrolled sources and fractional efficiency curves are not available in the 0.01-2 µ range, it was necessary to extrapolate available data to this size range (see Sections 5 and 6).

An alternate calculation method was employed as a cross check for some sources. For controlled sources, overall control equipment efficiency and particle size distributions at the exit of each type of control device can be used to calculate fine particle emissions. This method does not require use of control equipment fractional efficiency. However, as noted in Section 5.1, particle size distribution data for controlled sources are inadequate. As a result, utilization of the alternate procedure was restricted to those source categories where sufficient size distribution data for controlled sources were available.

7.1 Limited Check of the Validity of Particle Size and Fractional Efficiency Data Extrapolation

Because neither particle size distribution data nor fractional efficiency curves for control devices were available in the 0.01-2 µ size range, extrapolation of available data to this size range was necessary. Admittedly, such extrapolation casts doubt on the meaning and validity of the results of the fine particle emission calculations. The only satisfactory way to check the accuracy of such extrapolations would be to measure the requisite data in the appropriate size range and compare them with the extrapolated values. Since no experimental work could be performed in the current program, other methods of providing a check on the extrapolations were sought.

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In general, it was difficult to check the validity of the extrapolation technique because of inadequate sampling of fine particulates emitted from both uncontrolled and controlled sources. However, it was possible to perform a limited check on the technique by using data obtained by Bush on particle size distributions before and after an electrostatic precipitator operating on a pulverized coal-fired power plant.[14] Three items were used in performing the check:

1. Particle size distributions from uncontrolled power plants with pulverized coal-fired boilers (Bahco data, standard sampling methods).

2. Data obtained by Bush on particle size distributions before and after an electrostatic precipitator operating on a pulverized coal-fired unit. A thermal precipitator was used as the sampling device, and an electron microscope was used for particle sizing.[14]

3. The fractional efficiency curve for a medium efficiency electrostatic precipitator is shown in Figure 17.

Figure 18 summarizes the size distribution data for particulates emitted from uncontrolled units. The three curves on the left-hand side of Figure 18 are the complete size distributions as determined by Bahco methods (extreme and arithmetic average). The curves are the composite of over 300 individual size distributions for pulverized coal-fired power plants. The solid lines on the left-hand curves connect the actual measured size distributions, while the dashed lines are the linear extrapolation of the data down to the submicron range. Bush's data are given by the circles on the curve to the extreme right. In Bush's sampling arrangement, the inlet to the thermal precipitator was arranged so that particles above 5 μ diameter did not enter the precipitator. For the purposes of comparison, the < 5 μ data from the Bahco analysis were plotted on the same basis as the Bush data. The curve depicted by the solid squares and triangles illustrates the Bahco data in that form.

A comparison between the < 5 μ curve for the Bahco data, and Bush's data shows that the Bahco data are biased toward the large particle sizes. This is not surprising because of the inherent limitations of the Bahco device and the standard sampling techniques in the < 5 μ size range (see Appendix A). The thermal precipitator, on the other hand, is highly efficient in that size range. It deposits virtually all particles of most materials from 5 μ down to 0.01 μ. In addition, Bush used an electron microscope for the particle sizing. In view of the superior techniques utilized by Bush, the agreement between the two sets of data is considered quite good.

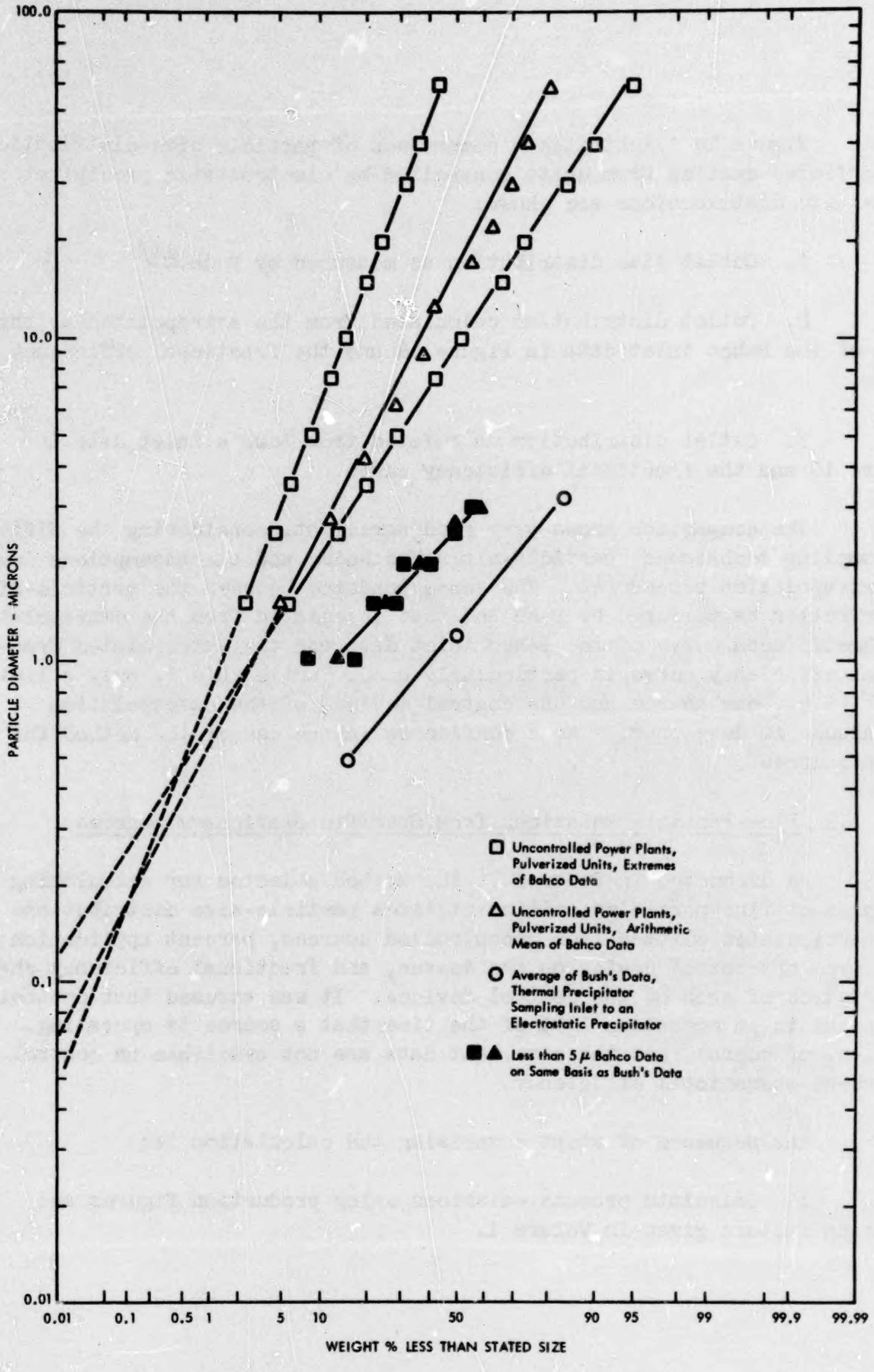

Figure 18 - Particle-Size Distributions of Particulates Emitted from Uncontrolled Power Plants (pulverized coal-fired boilers)

Figure 19 illustrates a comparison of particle size distributions of particles emitted from units controlled by electrostatic precipitators. Three size distributions are shown:

1. Outlet size distribution as measured by Bush.[14]

2. Outlet distribution calculated from the extrapolated arithmetic mean of the Bahco inlet data in Figure 18 and the fractional efficiency curve.

3. Outlet distribution calculated from Bush's inlet data in Figure 18 and the fractional efficiency curve.

The comparison shows very good agreement, considering the differences in sampling techniques, particle-sizing methods, and the assumptions involved in extrapolation procedures. The correspondence between the particle-size distribution as measured by Bush and that calculated from the extrapolated arithmetic mean curve of the Bahco inlet data and the extrapolated fractional-efficiency curve is particularly good. While this is only a limited check (i.e., one source and one control device) of the extrapolation technique, it does provide some confidence in the use of the method for other sources.

7.2 Fine-Particle Emissions from Specific Stationary Sources

As discussed in Section 7, the method selected for calculating the mass of fine particles emitted utilizes particle-size distributions for particulates emitted from uncontrolled sources, percent application of each type of control device on the source, and fractional efficiency characteristics of each of the control devices. It was assumed that control equipment is in operation 100% of the time that a source is operating. This is, of course, not the case, but data are not available on control equipment operational efficiency.

The sequence of steps comprising the calculation is:

1. Calculate process emissions using production figures and emission factors given in Volume I.

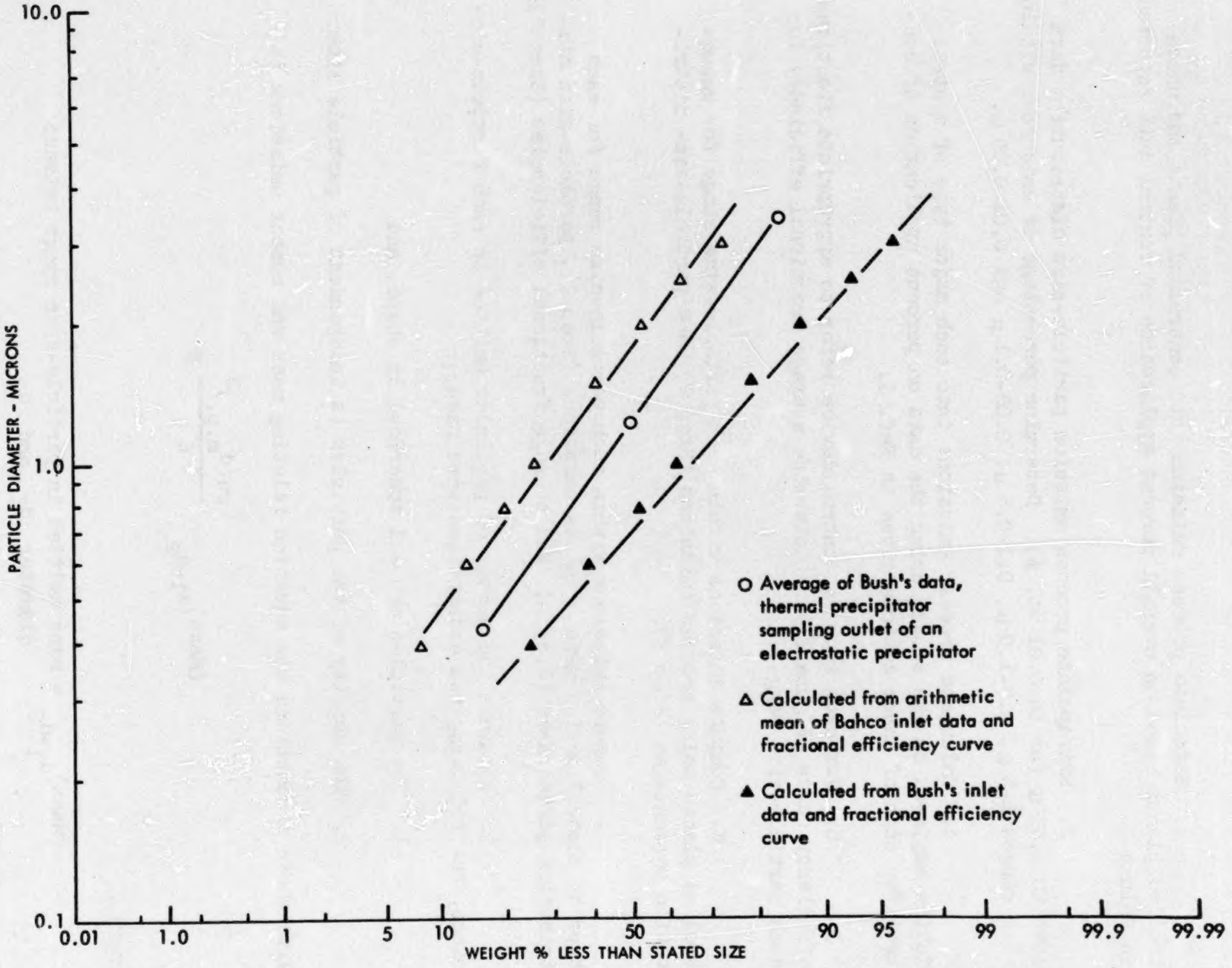

Figure 19 - Particle-Size Distributions of Particulates Emitted from Electric Utility Power Plants Controlled by Electrostatic Precipitators

2. Calculate process emission into controlled plants and uncontrolled plants based on overall percent application of control data reported in Volume I.

3. Extrapolate process emission particle-size distribution data down to 0.01 μ (or to 0.01 wt. %). Determine percentage of emissions within size ranges 1-3 μ, 0.5-1.0 μ, 0.1-0.5 μ, 0.05-0.1 μ and 0.01-0.05 μ.

4. Calculate process emissions into each major type of control device employed on the source using the data on percent application of control for each of these devices given in Ref. 1.

5. For each type of control device refer to appropriate fractional efficiency curve (Figure 17) to determine average fractional efficiency for each particle-size range.

6. Compute emissions within each particle-size range for uncontrolled plants using process emissions (Step 2), and particle-size distribution percentages (Step 3).

7. Compute emissions within each particle-size range for each type of control device using process emissions (Step 2), particle-size distribution percentages (Step 3), and average fractional efficiencies (Step 5).

To calculate the number of particles emitted in each particle-size range, the following two assumptions were made:

1. The particles are all spherical in shape, and

2. The density of the particles is independent of particle size.

With these assumptions the equation relating mass and number emissions is

$$(\text{Mass})_{d_1-d_2} = \frac{\rho\pi(d_{m.p.})^3}{6} N$$

where

$(\text{Mass})_{d_1-d_2}$ = mass emitted in particle-size range between diameter d_1 and d_2

ρ = particle density

$d_{m.p.}$ = particle diameter midpoint between d_1 and d_2

N = number of particles emitted with average diameter $d_{m.p.}$

The fine particle emissions for stationary sources for which adequate information was available are presented in Tables 1 and 2, pages 4 to 7. Summary comments on Tables 1 and 2 are given on pages 2 to 9. More details of the calculations for individual sources are presented in the following sections. The source categories are presented in the same sequence as the sources are listed in Table 1.

7.2.1 Stationary combustion sources:

7.2.1.1 Electric utilities--coal-fired boilers: Fine-particle emissions from electric utility coal-fired boilers are summarized in Table 8. Total emission of particulates < 2 μ is estimated to be 971,500 tons/year, which is about 31% of the total mass emissions for these boilers as reported in Table 4.1-1, Volume I. Fine-particle emissions for pulverized coal-fired boilers are presented in more detail in Tables E-74 to E-79, pages 303 to 308. Emmissions for stoker coal-fired boilers are shown in Tables E-80 to E-84, pages 309 to 313, while those for cyclone coal-fired boilers are summarized in Tables E-85 to E-89, pages 314 to 318.

Particle-size distributions for the various uncontrolled boilers are presented in Figures 20, 21, and 22. The data for pulverized coal-fired boilers in Figure 20 represent size distributions from more than 300 individual boilers. Figure 21 represents data from seven cyclone coal-fired boilers, while Figure 22 summarizes particle-size distributions obtained from nine stoker coal-fired boilers. Percent application of control and the percent controlled by different control devices was obtained from Section 5.1, Volume I.

7.2.1.2 Electric utilities--oil and gas-fired boilers: Accurate size data were not available for the particulates emitted from oil and gas-fired boilers, either for electric utility or industrial units. The meager data available indicated that emitted particulates were generally 90 wt. % less than 2 μ. Available information also indicates that these units are nearly all uncontrolled. Tables E-105 and E-106 present details of an estimate of the fine-particle emissions from both electric utility and industrial units. Emissions are estimated to be about 224,000 tons/year.

7.2.1.3 Industrial power plants--coal-fired boilers: Details of the calculations of fine-particle emissions from pulverized coal-fired industrial power plants are summarized in Tables E-90 to E-94, pages 319 to 323, for stoker coal-fired boilers in Tables E-95 to E-99, pages 324 to 328, and for cyclone coal-fired boilers in Tables E-100 to E-104, pages 329 to 333. Emissions of fine particulate are estimated to be 106,000 tons/year, which represents about 4% of the total mass emissions for these boilers as reported in Table 4.1-1, Volume I.

TABLE 8

SUMMARY OF FINE-PARTICLE EMISSIONS FROM STATIONARY FUEL COMBUSTION SOURCES

Source	Fine Particle Size Ranges (μ) 1-3	0.5-1.0	0.1-0.5	0.05-0.1	0.01-0.05	Total
A. **Mass Basis**	Tons/Year					
Stationary Fuel Combustion						
A. Coal						
1. Electric Utility						
a. Pulverized	591,600	178,600	99,200	2,900	--	872,300
b. Stoker	21,700	5,700	2,200	--	--	29,600
c. Cyclone	48,200	13,900	7,300	200	--	69,600
2. Industrial						
a. Pulverized	15,100	500	--	--	--	15,600
b. Stoker	56,600	7,300	2,100	--	--	66,000
c. Cyclone	13,500	6,700	4,100	100	--	24,400
B. Fuel Oil						
1. Electric Utility and Industrial	126,900	--	--	--	--	126,900
C. Natural Gas and LPG						
1. Electric Utility and Industrial	97,200	--	--	--	--	97,200
Total	970,800	212,700	114,900	3,200	--	1,301,600
B. **Number Basis**	Particles/Year					
A. Coal						
1. Electric Utility						
a. Pulverized	5.1×10^{22}	29.5×10^{22}	250×10^{22}	480×10^{22}		765×10^{22}
b. Stoker	0.2×10^{22}	0.9×10^{22}	5.6×10^{22}			6.7×10^{22}
c. Cyclone	0.42×10^{22}	2.3×10^{22}	18.5×10^{22}	83×10^{22}		104×10^{22}
2. Industrial						
a. Pulverized	0.3×10^{22}	0.08×10^{22}				0.38×10^{22}
b. Stoker	0.5×10^{22}	1.2×10^{22}	5.6×10^{22}			7.3×10^{22}
c. Cyclone	0.12×10^{22}	1.1×10^{22}	10.4×10^{22}	42×10^{22}		53.6×10^{22}
B. Fuel Oil						
1. Electric Utility and Industrial	1.1×10^{22}					1.1×10^{22}
C. Natural Gas						
1. Electric Utility and Industrial	0.85×10^{22}					0.85×10^{22}
Total	8.6×10^{22}	35.1×10^{22}	290.1×10^{22}	605×10^{22}		939×10^{22}

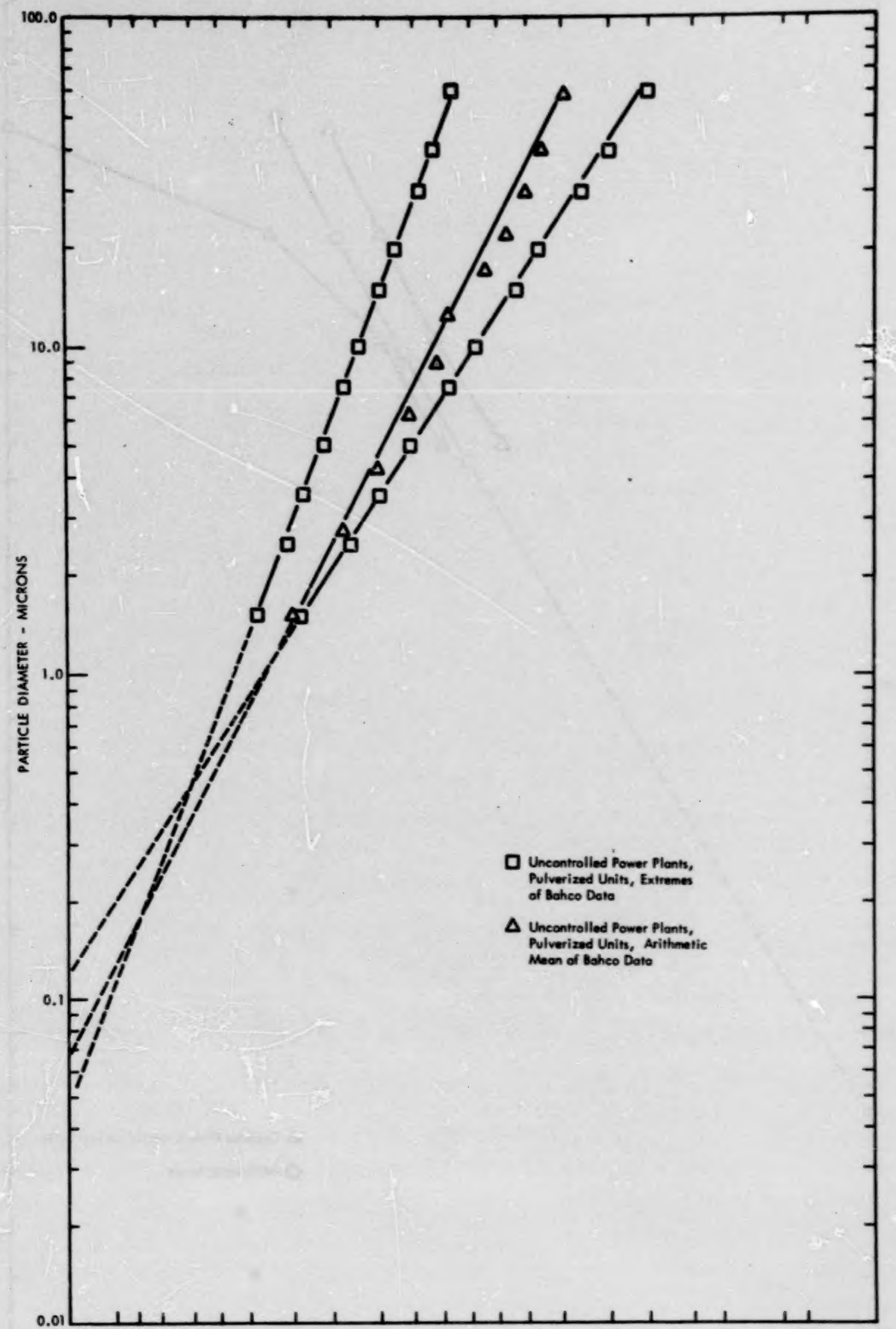

Figure 20 - Particle-Size Distributions of Particulates Emitted from Uncontrolled Power Plants (pulverized coal-fired boilers)

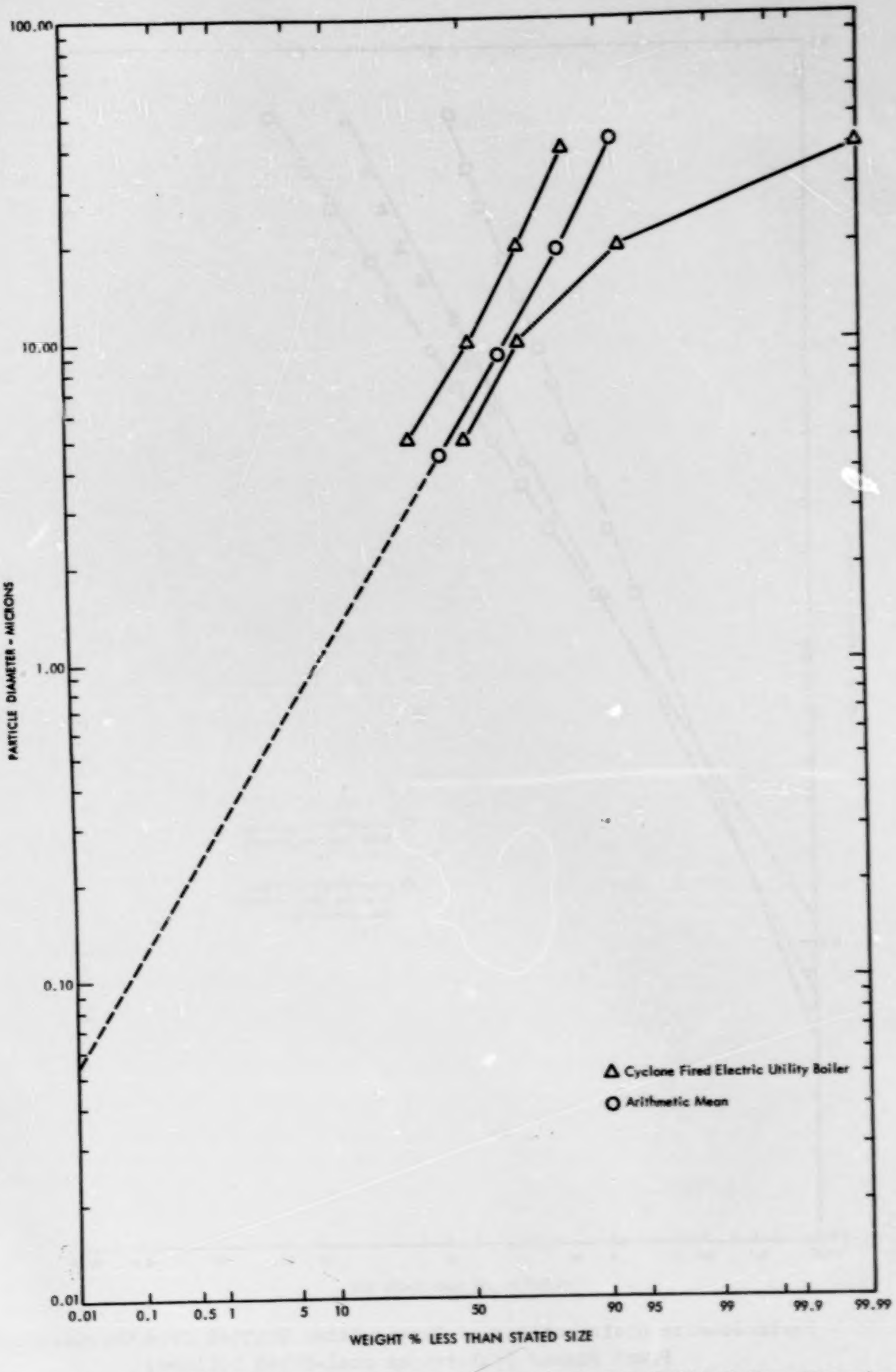

Figure 21 - Particle-Size Distributions of Particulates Emitted from Uncontrolled Power Plants (cyclone coal-fired boilers)

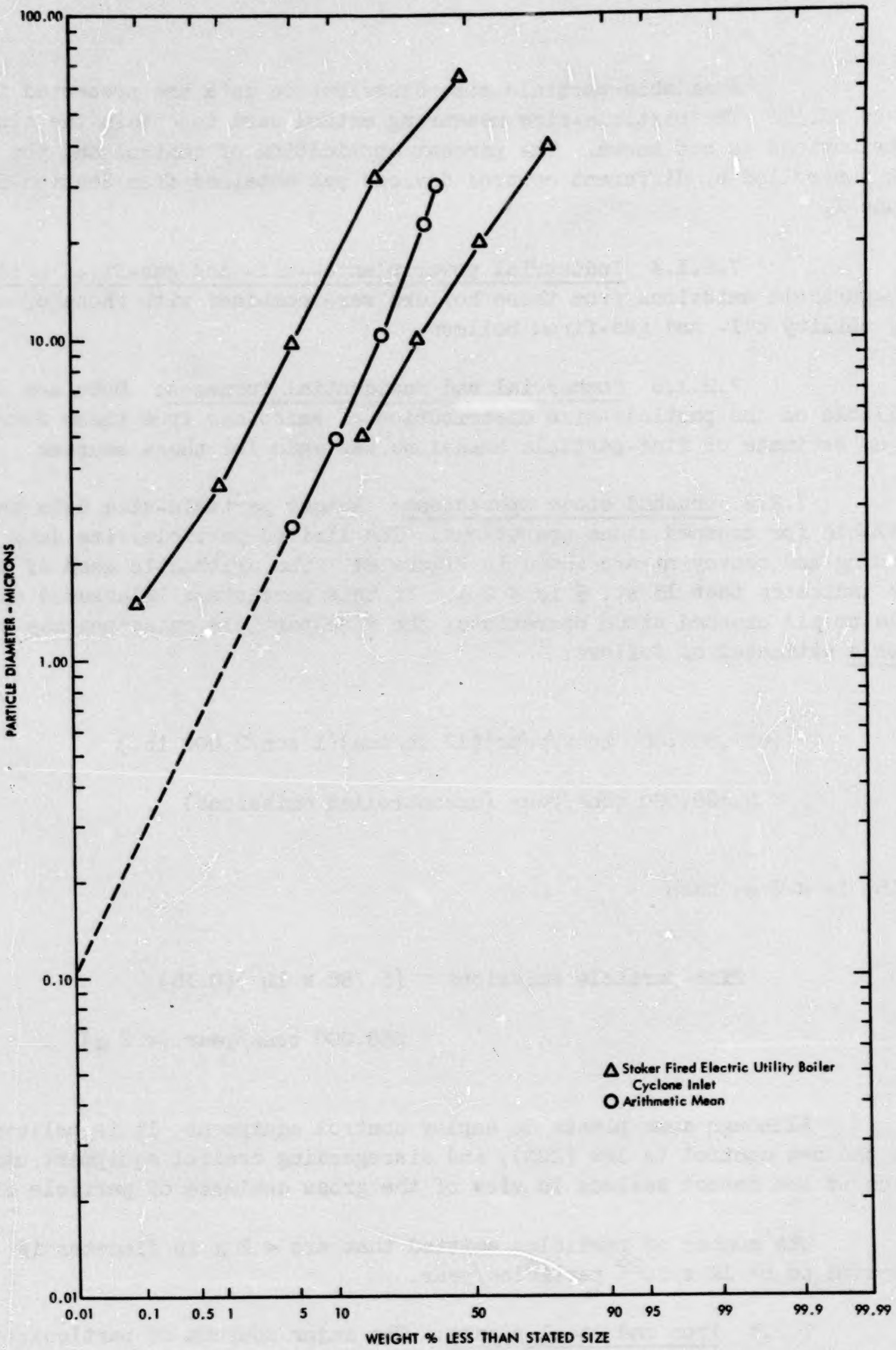

Figure 22 - Particle-Size Distribution of Particulates Emitted from Uncontrolled Power Plants (stoker coal-fired boilers)

Available particle-size distribution data are presented in Figure 23.[15] The particle-size measuring method used to obtain the size distributions is not known. The percent application of control and the percent controlled by different control devices was obtained from Section 5.1.2, Volume I.

7.2.1.4 Industrial power plants--oil- and gas-fired boilers: Fine-particle emissions from these boilers were combined with those of electric utility oil- and gas-fired boilers.

7.2.1.5 Commercial and residential furnaces: Data are not available on the particle-size distribution of emissions from these sources and no estimate of fine-particle emissions was made for these sources.

7.2.2 Crushed stone operations: Meager particle-size data are available for crushed stone operations. The limited particle-size data for crushing and conveying are shown in Figure 24. The arithmetic mean of these data indicates that 15 wt. % is $< 2\ \mu$. If this percentage is assumed applicable to all crushed stone operations, the fine-particle emissions may be grossly estimated as follows:

$$(681{,}000{,}000 \text{ tons/year})(17 \text{ lb/ton})(1 \text{ ton}/2{,}000 \text{ lb.})$$

$$= 5{,}788{,}000 \text{ tons/year (uncontrolled emissions)} \quad .$$

If 15% is $< 2\ \mu$, then

$$\text{fine-particle emissions} = (5.788 \times 10^6)(0.15)$$

$$= 868{,}000 \text{ tons/year } (< 2\ \mu) \quad .$$

Although some plants do employ control equipment, it is believed that the net control is low (20%), and disregarding control equipment utilization is not deemed serious in view of the gross estimate of particle size.

The number of particles emitted that are $< 2\ \mu$ in diameter is estimated to be 19×10^{22} particles/year.

7.2.3 Iron and steel plants: The major sources of particulate air pollution in iron and steel plants are: sintering machines, coke-oven plants, blast-furnace operations, steel-making furnaces, and materials handling operations. Fine-particle emissions were estimated only for

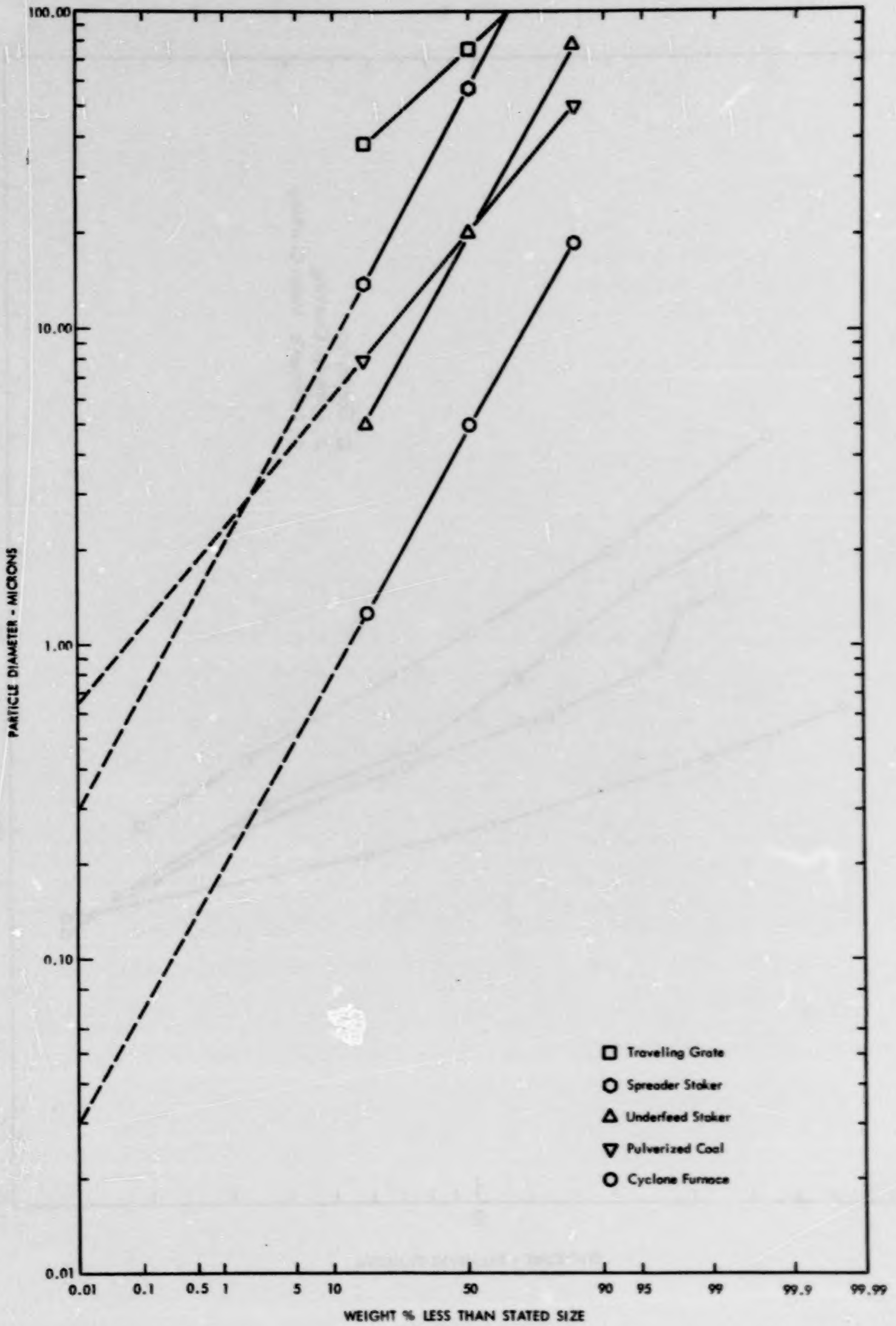

Figure 23 - Particle-Size Distributions of Particulates Emitted from Uncontrolled Industrial Power Plants (coal-fired)

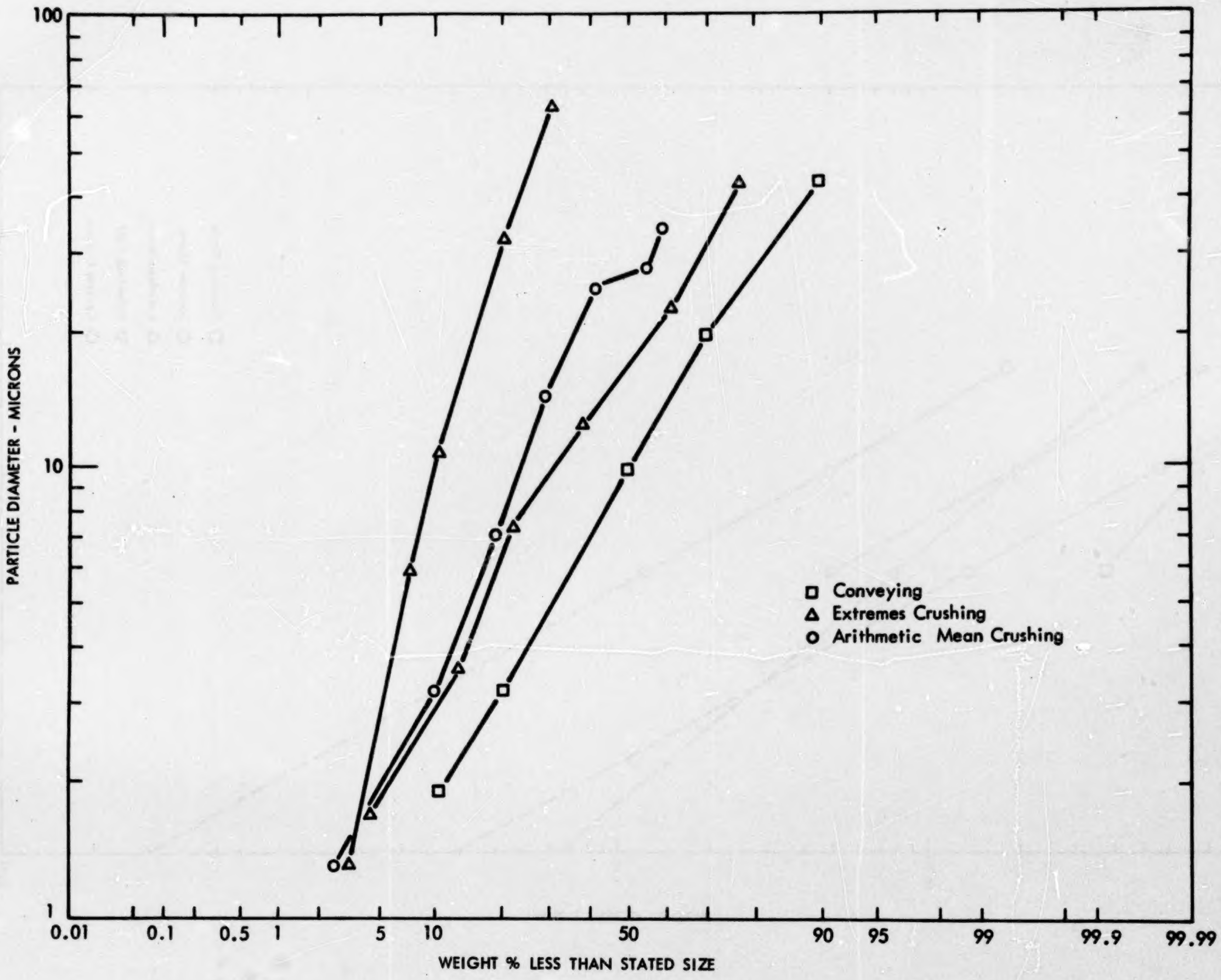

Figure 24 - Particle-Size Distribution of Particulates Emitted from Uncontrolled Crushed Stone Operations (Bahco data)

sintering machines and steel-making furnaces because of lack of particle-size distribution data for the other sources. Table 9 summarizes the estimates that were made for this industry. The emission calculations for sinter machines and steel-making furnaces are reviewed in the following sections.

7.2.3.1 Sinter machines: Details of the calculation of fine-particle emissions from sinter machines are presented in Tables E-40 to E-43, pages 269 to 272. The 5,600 tons/year listed in Table 9 is about 5% of the total mass emissions for these machines (Table 4.1-1, Volume I).

Particle-size distributions for uncontrolled and controlled sinter machines are illustrated in Figure 25. Information on percentage application of control was obtained from the telephone survey reported in Section 5.4, Volume I.

Fine-particle emissions from sinter machines controlled by cyclones were calculated using particle-size distributions from both uncontrolled and controlled units. Utilizing particle-size distributions from uncontrolled sinter machines and the high efficiency cyclone curve in Figure 17, emissions were estimated to be 5,100 tons/year. This compares with 9,200 tons/year obtained using particle-size distributions from controlled units, and the assumption that cyclones used on the sinter machines have an overall efficiency of 80%.

7.2.3.2 Open hearth furnaces: Estimates of the fine-particle emissions from open hearth furnaces proved to be difficult because data on particle-size distributions from uncontrolled or controlled furnaces are almost nonexistent. Furthermore, there are inconsistencies in the available information. Another complication is that the mass rate of emissions, and the particle size of the emitted material changes during the furnace cycle.

Figure 26 illustrates both of these aspects of available particle-size data. The two curves in the upper left represent data from a furnace utilizing an oxygen lance.[16] The sampling method and particle sizing method are not known. The data in the lower right of Figure 26 were obtained by using two sampling trains:

1. Glass cloth thimble ahead of a Whatman paper thimble, and

2. A thermal precipitator.

Particle sizing was accomplished by optical techniques. The samples were collected between charging periods and early in the melting period.

TABLE 9

SUMMARY OF FINE-PARTICLE EMISSIONS FROM IRON AND STEEL PLANTS

Source	Particle Size Ranges (μ)					
	1-3	0.5-1.0	0.1-0.5	0.05-0.1	0.01-0.05	Total
A. Mass Basis	Tons/Year					
1. Sinter Machine	3,800	1,200	600			5,600
2. Steel-Making Furnaces						
a. Open Hearth*	60,500-80,000	19,600-55,500	8,500-234,200	100-22,100	0-3,600	108,200-375,900
b. Basic Oxygen*	900	18,900	153,700	1,000		174,500
c. Electric Arc	3,800	2,500	5,200	1,300	1,500	14,300
Totals	69,000-88,500	42,200-78,100	168,000-393,700	2,400-24,400	1,500-5,100	302,600-570,300
B. Number Basis	Particles/Year					
1. Sinter Machine	2.74 x 10^{20}	16.5 x 10^{20}	128 x 10^{20}			147.2 x 10^{20}
2. Steel-Making Furnaces						
a. Open Hearth	2.62-3.48 x 10^{21}	16.2-45.8 x 10^{21}	109-3,000 x 10^{21}	0.83-180 x 10^{23}	0-4.6 x 10^{25}	2.1-670 x 10^{23}
b. Basic Oxygen	5.6 x 10^{20}	22.2 x 10^{21}	2.82 x 10^{24}	1.08 x 10^{24}		3.92 x 10^{24}
c. Electric Arc	2.1 x 10^{20}	26.4 x 10^{20}	8.5 x 10^{22}	1.37 x 10^{24}	24.7 x 10^{24}	26.2 x 10^{24}
Totals	36.6-45.2 x 10^{20}	427-723 x 10^{20}	302.7-592 x 10^{22}	25.3-204.5 x 10^{23}	2.47-4.6 x 10^{25}	3-9.7 x 10^{25}

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* See Sections 7.2.3.2 and 7.2.3.3 for discussion of calculation of fine-particle emissions from open hearth and basic oxygen furnaces.

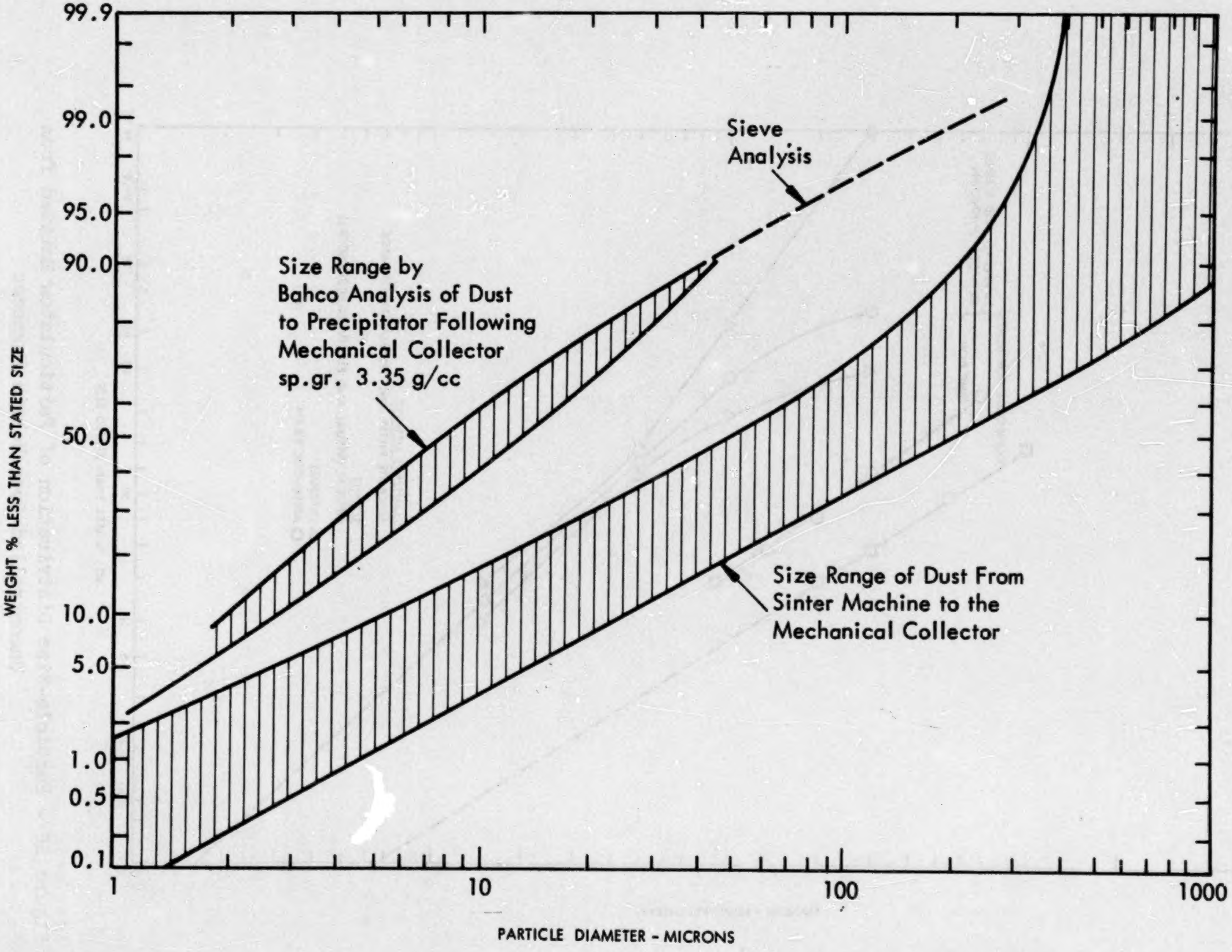

Figure 25 - Particle-Size Distribution by Weight of Sintering Machine Dust

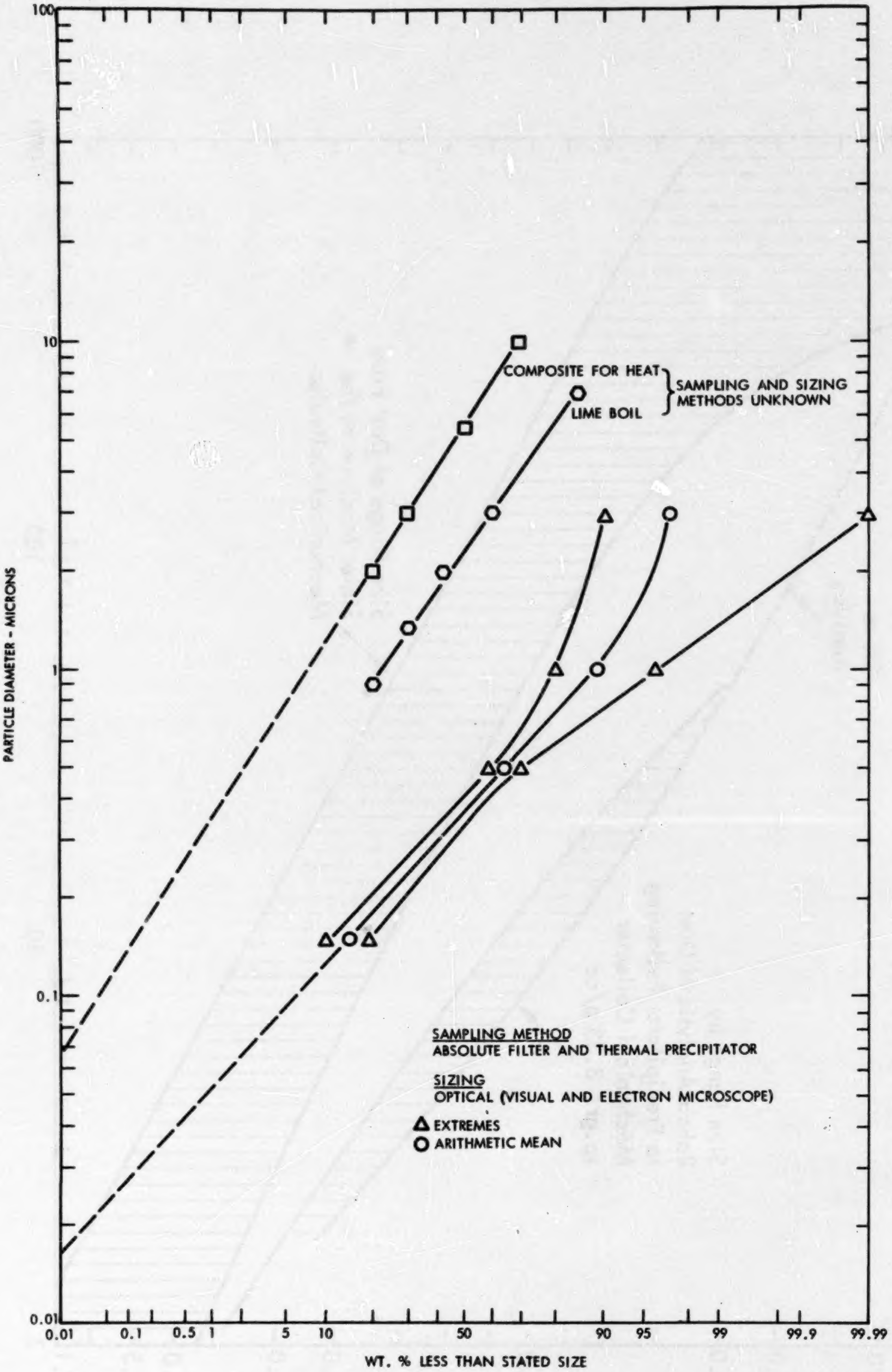

Figure 26 - Particle-Size Distribution of Particulates Emitted from Uncontrolled Open Hearth Furnaces

Fine particle emissions for open hearth furnaces were calculated using both sets of data in Figure 26. Tables E-36 to E-39, pages 265 to 268 , summarize the calculations. Emissions are estimated to be 375,900 tons/year, using the particle size data in the lower right of Figure 26. This quantity exceeds the 337,000 tons/year reported as the total mass emissions from these furnaces (Table 4.1-1, Volume I).

If the "composite" particle-size distribution (upper left) in Figure 26 is used for the calculations, the emissions are estimated to be 108,200 tons/year.

The discrepancy in the emission figures indicates that:

1. The particle-size distributions are erroneous, or

2. The overall efficiency of the electrostatic precipitators and/or the degree of application of control reported in Section 5.4, Volume I, is too high.

Additional field testing of open-hearth furnaces and associated control equipment will be necessary to pinpoint the exact cause of the above inconsistency.

7.2.3.3 Basic oxygen furnaces: Calculations of fine-particle emissions from basic oxygen furnaces were also hampered by a discrepancy in the reported particle-size distributions for basic oxygen furnace dust. Reports have been made of 95% < 1 μ as well as 99% < 0.2 μ. Available particle size data are presented in Figure 27. The curve with the triangle symbols was used for the emission calculations.

Tables E-26 to E-29, pages 255 to 258, summarize the calculation of emissions. Emissions are estimated to exceed 174,000 tons/year. This quantity is nearly 20 times as high as that reported for total mass emissions from basic oxygen furnaces in Table 4.1-1, Volume I. This discrepancy results primarily from the calculation of fine-particle emissions from BOF units controlled with Venturi scrubbers (Table E-29, page 258).

The emissions from BOF units that are controlled with Venturi scrubbers were computed using the particle-size distribution for uncontrolled furnaces (Figure 27), and the fractional efficiency curve for a Venturi scrubber (Figure 17). Since all available information indicates that the particulate emitted from these furnaces is nearly all micron or submicron in size, the large difference in the computed emissions appears to result from the fractional efficiency values for the Venturi scrubber given in Figure 17. The fractional efficiency curve for a Venturi scrubber indicates a collection efficiency of 92% for 1-μ particles, 88% for 0.5-μ particles,

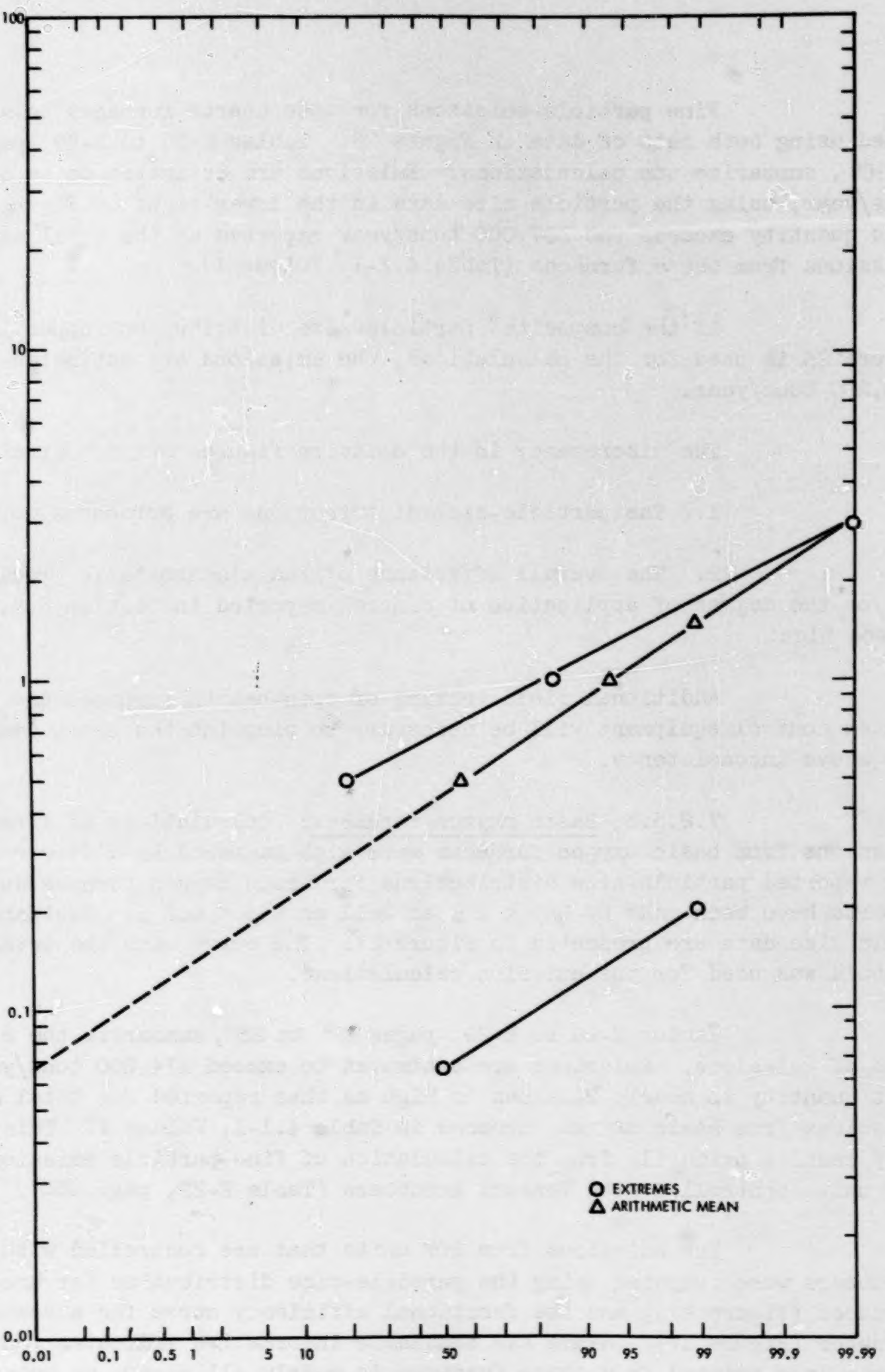

Figure 27 - Particle-Size Distribution of Particulates Emitted from Uncontrolled Basic Oxygen Furnaces

and 22% for 0.1-μ particles. The particle-size distribution for basic oxygen furnace dust (Figure 27) shows 94% < 1 μ and 58% < 0.5 μ. Comparing this particle-size distribution with the respective Venturi scrubber efficiencies indicates that the overall efficiency for a Venturi scrubber would be less than 88% on a typical basic oxygen furnace. This value of overall efficiency for a Venturi scrubber on BOF emissions seems quite low, particularly in view of field tests on Venturi scrubbers operating on BOF units that indicate 96-99% overall efficiency.[56,57]

Difficulties in sampling the outlet of Venturi scrubbers on basic oxygen furnaces may have led to erroneous conclusions regarding the overall efficiency. The exact sampling procedures used in the field tests were not defined. As discussed in Appendix A, standard sampling techniques are not adequate for sampling submicron particulates. If standard sampling trains were employed, it is possible that a significant portion of the particulate leaving the scrubber was not collected. Failure to collect part of the material leaving the scrubber would result in the calculation of a higher than actual efficiency for the control device.

An effort was made to check the fractional efficiency curve for the Venturi scrubber by calculating theoretical particle penetration from information given in Reference 19. Assuming a liquid-to-gas ratio of 8 gal/mcf and a pressure drop of at least 40 in. H_2O, theoretical efficiencies of about 90% for 0.5-μ particles, and 95% for 1 μ particles were determined. These theoretical collection efficiencies compare quite well with the values indicated by the fractional efficiency curve of Figure 17. Different assumptions of pressure drop and liquid/gas ratio would, of course, alter the theoretical efficiencies.

Comparison of the fractional efficiency curve in Figure 17 with the theoretical and measured overall efficiencies does not resolve the large difference in the calculated emissions. This raises the possibility that the particle-size distributions for basic oxygen furnace dust are not correct. Meager data are available on the particle-size of BOF dust. Only two particle-size distributions were found during the program (Figure 27). Therefore, it is possible that the data shown in Figure 27 are not representative of BOF dust. However, telephone contacts with knowledgeable people in the iron and steel industry, indicated that primary BOF dust (i.e., unagglomerated) is predominantly submicron in size.[58,59]

It is also possible that the particle size which a control device "sees" is not the same as that reported in Figure 27. As noted in the preceding paragraph, the data in Figure 27 are assumed to represent primary particulates. BOF dust is mainly red iron oxide which has a high tendency to agglomerate. If the dust is transported through a hooding and ducting system before it enters a control device, considerable agglomeration may occur. In this event, the particles would be larger than shown in Figure 27, and the efficiency of a control device would be correspondingly higher. Also the fractional efficiency curve for a Venturi scrubber shown in Figure 17 was not obtained for a scrubber collecting basic oxygen furnace dust, but rather for a dust that had low agglomeration tendencies. In passage through a scrubber BOF dust may agglomerate more than a dust of lower agglomeration tendency. Therefore, the scrubber might exhibit a high efficiency because of the agglomeration characteristics of BOF dust.

All of the above factors probably contribute to the differences between the calculated total and fine-particle mass emissions. This case clearly indicates the many pitfalls involved in calculating fine-particle emissions from generalized fractional efficiency curves, extrapolated particle size data, and inadequate information on particulate sampling procedures. Resolution of the difference can be accomplished only by careful field testing of Venturi scrubbers on basic oxygen furnaces.

7.2.3.4 Electric arc furnaces: Limited particle-size data are available for the electric arc furnaces. As was the case with the other steel-making furnaces, there is also considerable spread between individual particle-size distributions. Figure 28 presents the available particle-size data. The arithmetic mean curve was used for the calculation of emissions which are summarized in Tables E-30 to E-35, pages 259 to 264. Fine-particle emissions are estimated at 14,300 tons/year, which is nearly 80% of the total mass emission (18,000 tons/year) reported in Table 4.1-1, Volume I.

7.2.4 Forest products industry: The forest products industry encompasses forestry, sawmill, plywood, particleboard, hardboard, and pulp mill operations. Only in the kraft pulp mill operations were sufficient particle-size and application-of-control data available to permit an estimate of the fine-particle emissions. Fine-particle emissions from kraft pulp mills are given in Table 10. Individual sources in the kraft pulp mills are discussed in the following sections.

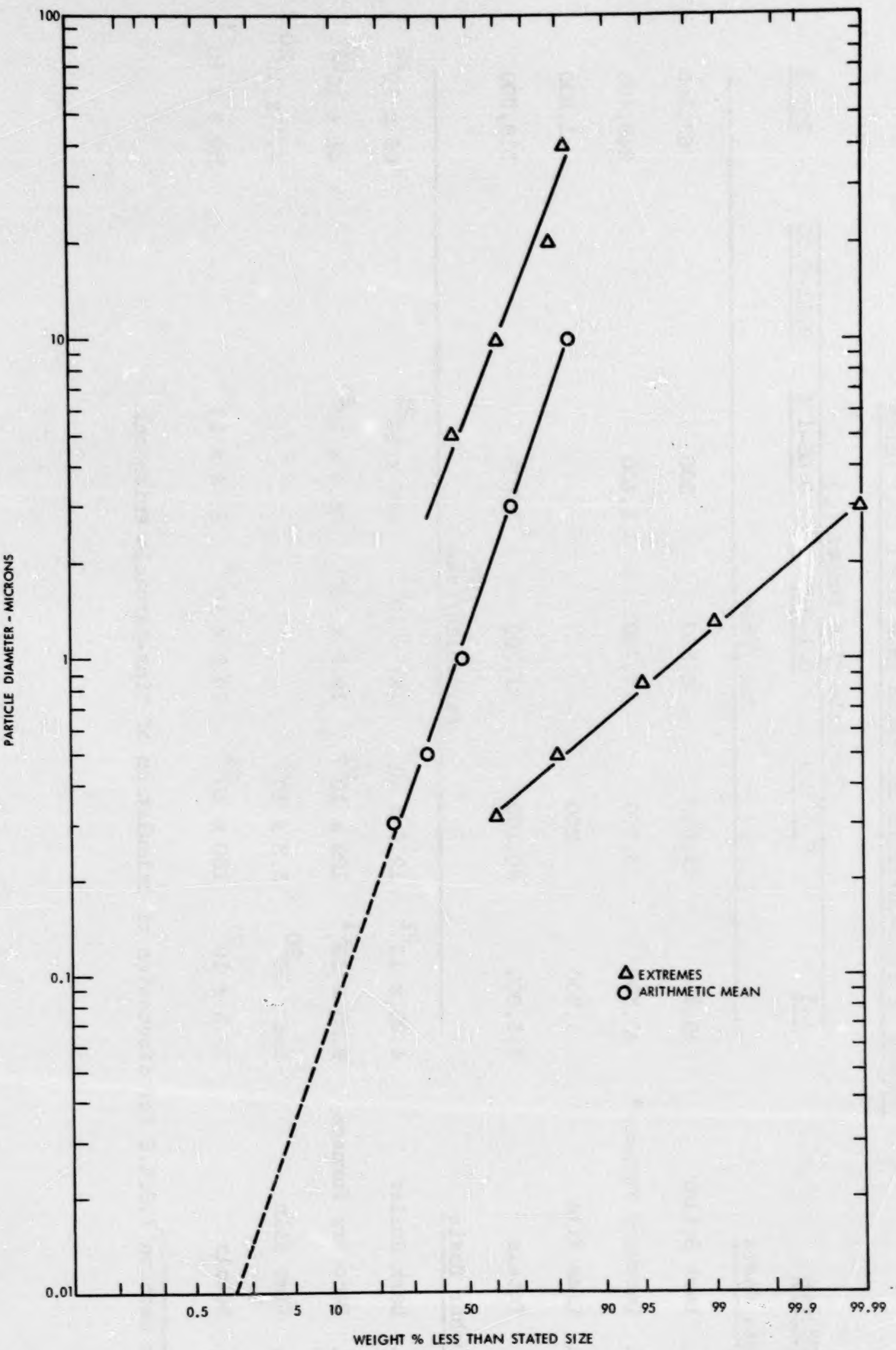

Figure 28 - Particle-Size Distribution of Particulates Emitted from Uncontrolled Electric Arc Furnaces

TABLE 10

SUMMARY OF FINE-PARTICLE EMISSIONS FROM KRAFT PULP MILLS

Source	Particle Size Ranges (μ) 1-3	0.5-1.0	0.1-0.5	0.05-1.0	0.01-0.05	Total
A. Mass Basis	Tons/Year					
1. Bark Boiler	49,100	11,900	6,500	300		67,800
2. Recovery Furnace*	95,300	78,000	74,700	1,400		249,400
3. Lime Kiln	1,600	200				1,800
Totals	146,000	90,100	81,200	1,700		319,000
B. Number Basis	Particles/Year					
1. Bark Boiler	4.25×10^{21}	19.6×10^{21}	167×10^{21}	500×10^{21}		69×10^{22}
2. Recovery Furnace	8.25×10^{21}	129×10^{21}	19.2×10^{23}	23.4×10^{23}		44×10^{23}
3. Lime Kiln	1.4×10^{20}	3.3×10^{20}				4.7×10^{20}
Totals	12.5×10^{21}	150×10^{21}	20.9×10^{23}	28.4×10^{23}		50.9×10^{23}

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* See Section 7.2.4.2 for discussion of calculation of fine-particle emissions.

7.2.4.1 Bark boilers: Many of the pulp mills utilize wood wastes as feed to the boiler plants. Reported particle-size distributions for particulate effluents from five separate uncontrolled bark boilers are presented in Figure 29. Tables E-50 to E-53, pages 279 to 282, summarize fine-particle emission calculations for the bark boilers. Emissions are estimated at 67,800 tons/year, or nearly 83% of the total mass emissions (82,000 tons/year) reported in Table 4.1-1, Volume I. Since cyclones are the main control device used on these boilers, emissions from controlled units would be mostly in the smaller particle-size ranges which is in general agreement with the estimate.

7.2.4.2 Recovery furnaces: The recovery furnace is the major source of particulate emissions in kraft pulp mills. Because of the extreme fineness, hygroscopic nature, and impaction characteristics of recovery furnace dust, it is difficult to collect a sample for size analysis. Available particle-size distribution data are presented in Figure 30. A small electrostatic precipitator[20] and a cascade impactor[2] were used for sampling. Particle sizing was performed with an electron microscope.

Most kraft pulp mills now use electrostatic precipitators to control emissions from recovery furnaces. In some cases, it has been noted that the particle collection efficiency of the electrostatic precipitator decreases for particles above 1.5-2.0 μ in diameter. Figure 31 illustrates collection efficiency as a function of particle size for a precipitator exhibiting such a decrease in efficiency with increasing particle size.[2] One reason for this occurrence is that electrostatic forces can coagulate small particles into large agglomerates. The giant particles can be reintroduced into the gas stream, and may or may not be recollected by downstream collection electrodes. This phenomenon of particle growth and subsequent reentrainment in the gas flow is dependent upon the physical character of the particulates. The physical characteristics of particulate emissions appear to be strongly dependent upon the flue gas temperature. In some furnaces, the dust is light and easily handled and transported in flue systems, while in other furnaces the dust is a sticky or heavy material which tends to build up in flue systems.

The extent to which the phenomenon depicted in Figure 31 occurs in recovery furnaces is not known and it was assumed negligible in the calculations of fine-particle emissions from these furnaces.

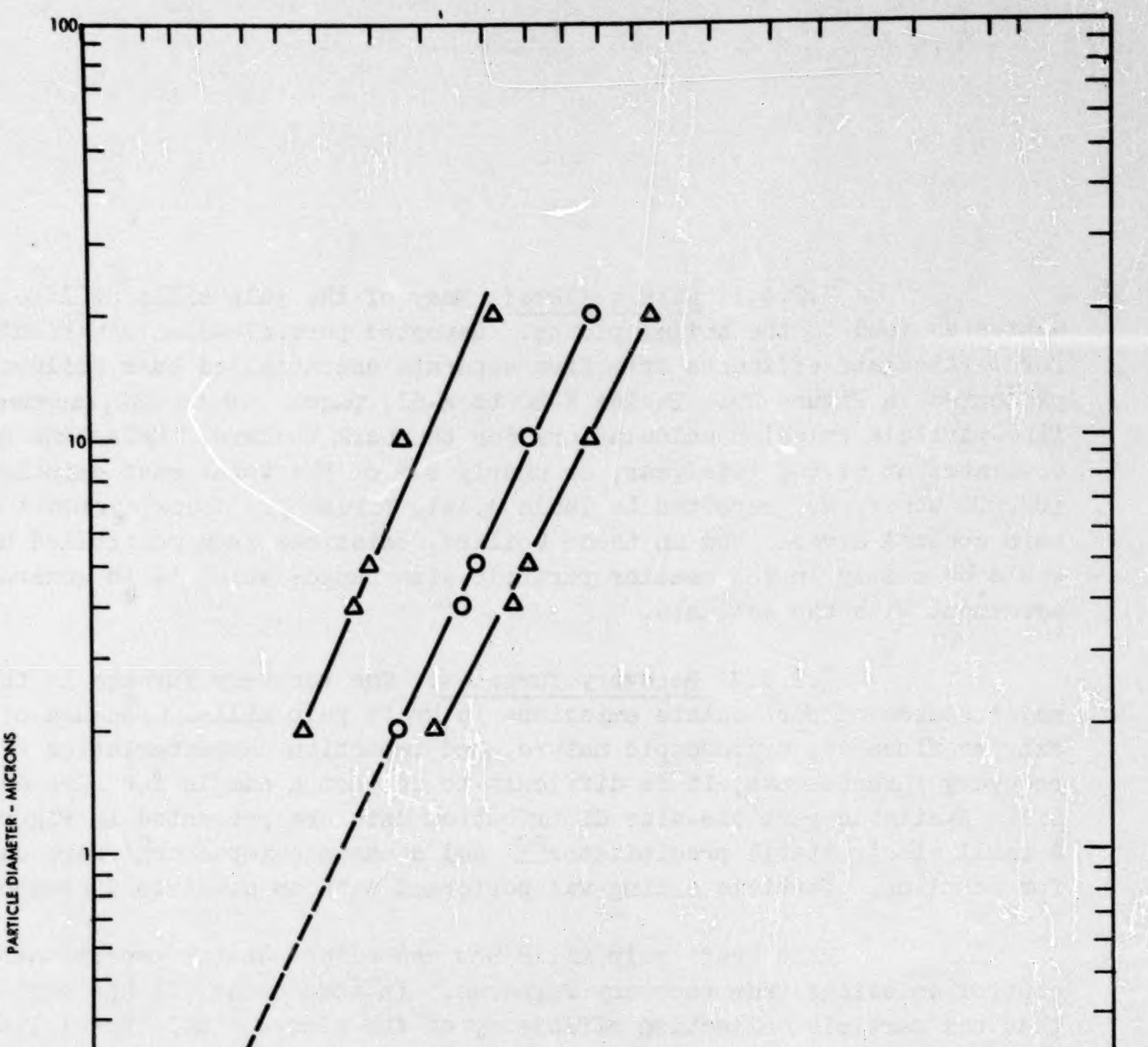

Figure 29 - Particle-Size Distribution for Particulates Emitted from Uncontrolled Pulp Mill Bark Boilers.(Bahco data)

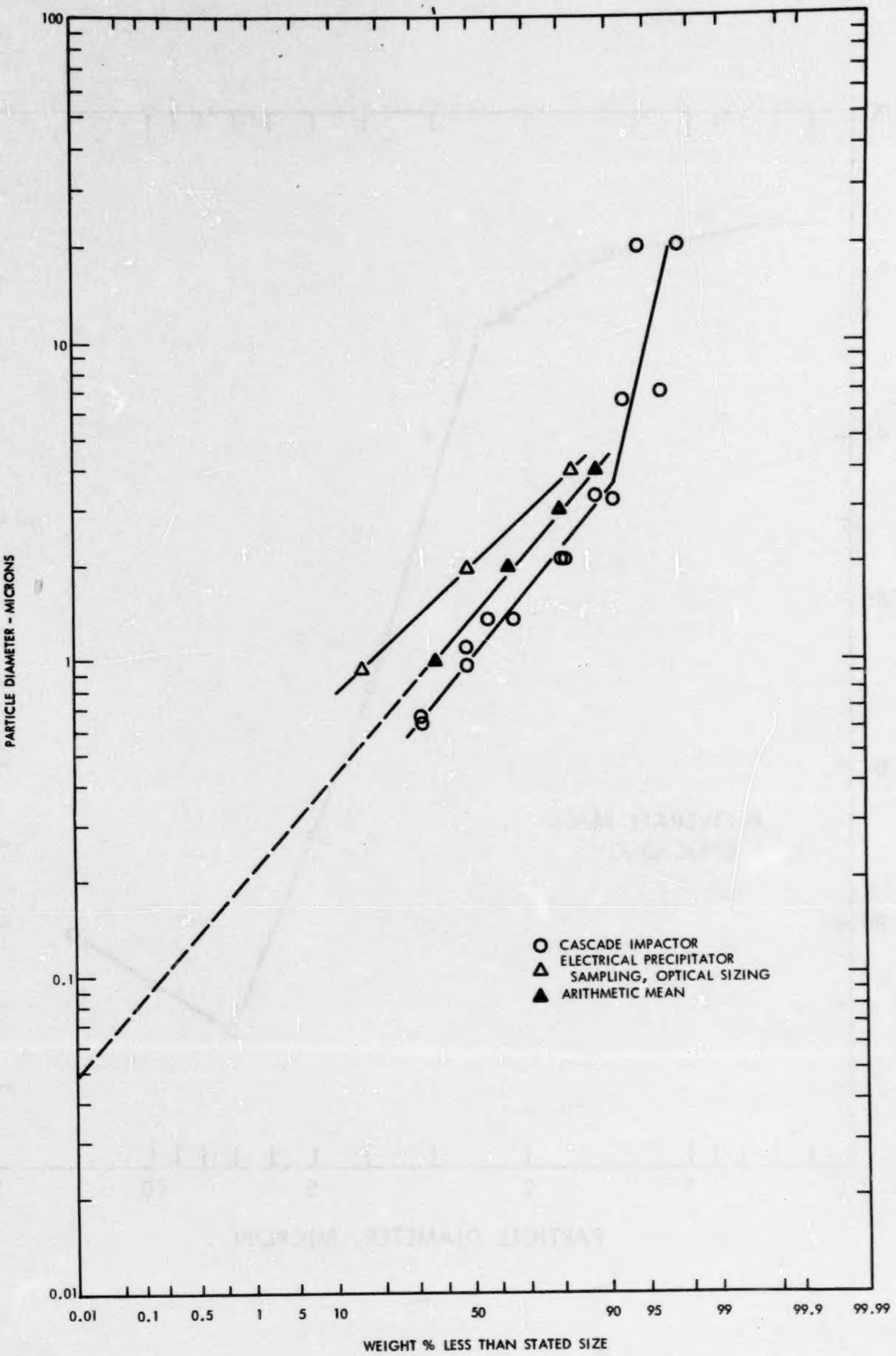

Figure 30 - Particle-Size Distribution for Particulates Emitted from Uncontrolled Pulp Mill Recovery Furnaces

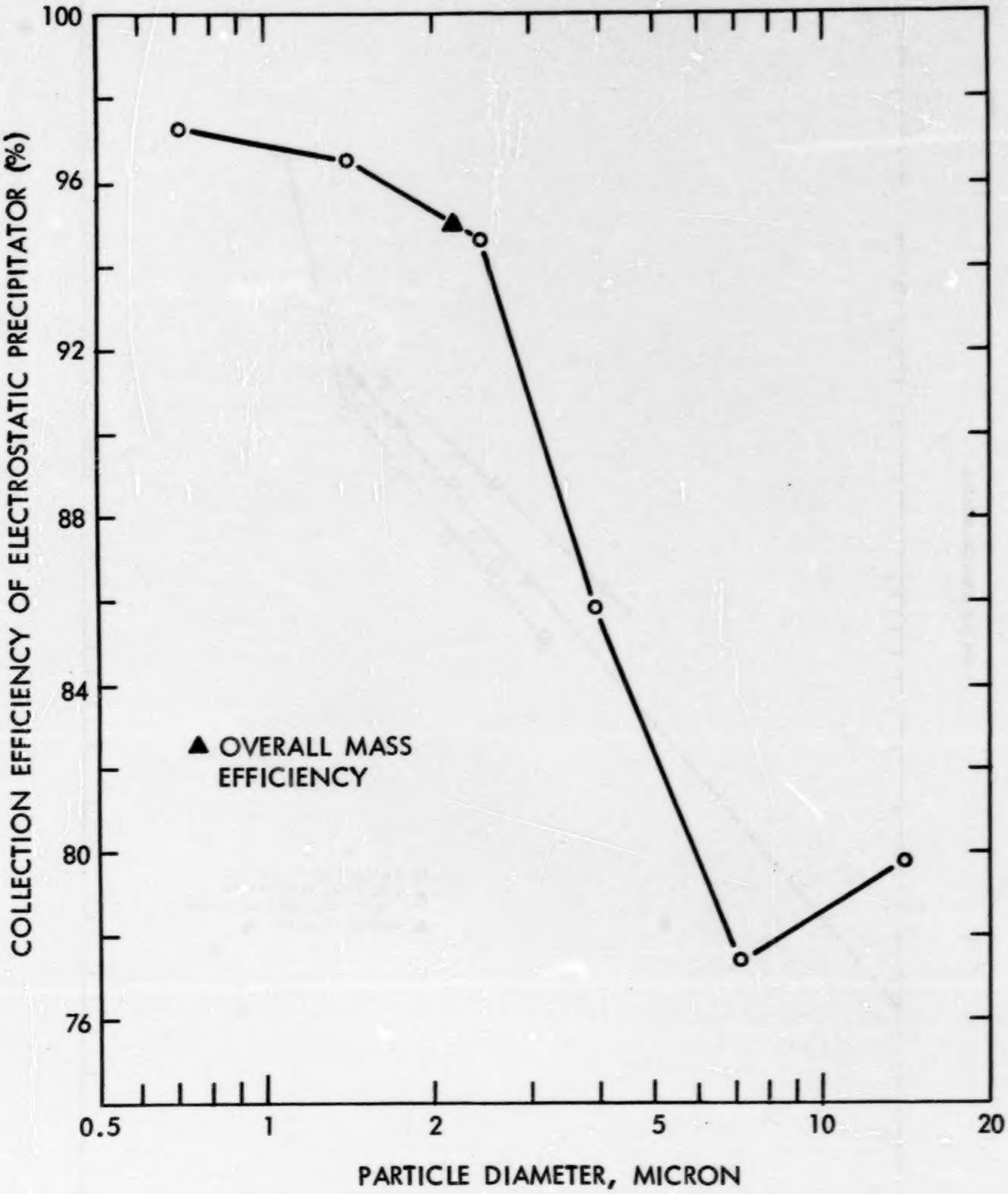

Figure 31 - Fractional Efficiency of an Electrostatic Precipitator Operating on a Kraft Mill Recovery Furnace[2]

Tables E-54 to E-57 summarize the estimates of emissions from recovery furnaces. As shown in Table E-57, using the fractional efficiency curve (Figure 17) for a medium efficiency electrostatic precipitator results in fine-particle emissions (234,500 tons/year) which exceed the total mass emissions (164,000 tons/year) listed in Table 4.1-1, Volume I. Using the fractional efficiency for a high efficiency electrostatic precipitator (Figure 17), emissions of 32,400 tons/year of fine particulate are calculated.

Available information on the performance characteristics of electrostatic precipitators on recovery furnaces indicates that overall efficiency probably does not exceed 95-97% (i.e., medium efficiency). This fact tends to support the use of the fractional efficiency curve for a medium efficiency precipitator to calculate fine-particle emissions.

Because of the variable character of the emitted particulate and observed decrease in equipment efficiency with increasing size, the discrepancy in emission figures cannot be resolved at this time. Additional field testing of electrostatic precipitators on recovery furnaces will be necessary.

7.2.4.3 Lime kilns: Data on particle-size distributions from either uncontrolled or controlled pulp mill lime kilns are nearly nonexistent. Figure 32 illustrates the only particle-size distribution that was found during the study.[17] The sampling technique used to obtain the material for subsequent particle sizing was not mentioned in Ref. 17. Microscopic techniques were used for the determination of the size distribution. Since an adequate number of particle-size distributions were not available, only a gross estimate of fine-particle emissions from lime kilns in pulp mills was made.

Tables E-58 to E-61, pages 287 to 290, summarize the calculation of fine-particle emissions for the lime kilns. Fine-particle emissions total only 1,800 tons/year, which is about 5.5% of the total mass emissions reported in Table 4.1-1, Volume I.

7.2.5 Cement plants: In the cement plant source category, calculations of fine-particle emissions could be performed only for the rotary kilns. Calculations of emissions from dryers, grinders, and other miscellaneous sources could not be done with any reliability because of lack of information on emission factors, particle-size distributions, and application of control.

Table 11 summarizes fine-particle emissions for rotary cement kilns. Production and emission factor data were taken from Section 4.6, Volume I. The overall percent of application of control and the percent controlled by different control devices was obtained from a telephone survey as reported in Volume I.

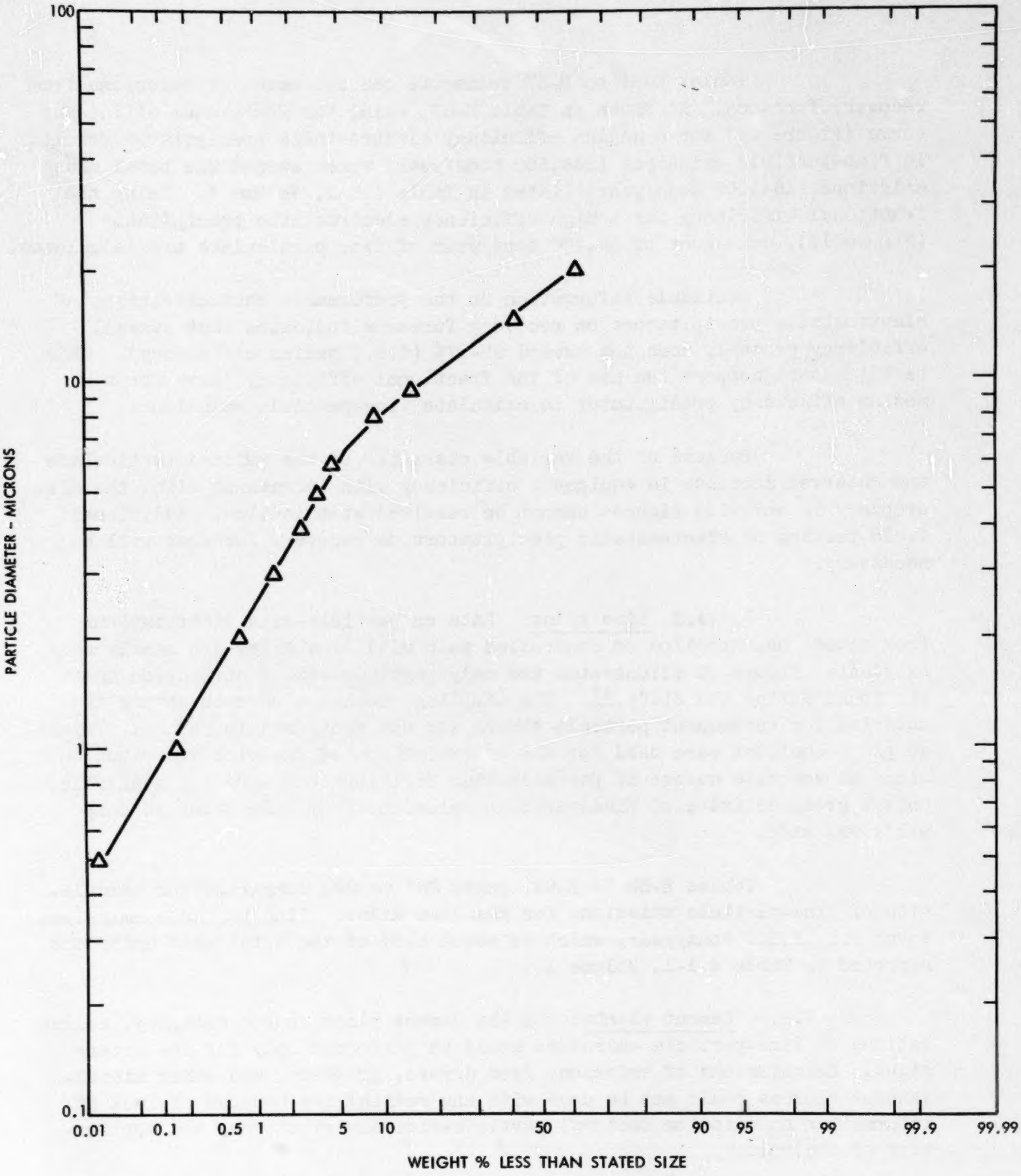

Figure 32 - Particle-Size Distribution of Particulates Emitted from Uncontrolled Pulp Mill Lime Kilns

TABLE 11

SUMMARY OF FINE-PARTICLE EMISSIONS FROM ROTARY CEMENT KILNS

	Particle Size Ranges (μ)					
	1-3	0.5-1.0	0.1-0.5	0.05-0.1	0.01-0.05	Total
A. Mass Basis	Tons/Year					
	130,800	32,700	13,500			177,000
B. Number	Particles/Year					
	9.7×10^{21}	46.4×10^{21}	3×10^{23}			3.5×10^{23}

In making these estimates the arithmetic mean (extrapolated to the lower particle sizes) of the particle-size distribution data for uncontrolled sources (Figure 33) was used. The data in Figure 33 represent the composite of size distributions obtained from 42 individual kilns. Figure 34 presents particle-size data for particulates emitted from controlled kilns. Details of the calculation of the fine particle emissions are given in Tables E-11 to E-17, pages 240 to 246.

7.2.6 Hot-mix asphalt paving plants: Asphalt is a raw material for several industries. Two of the more important with regard to air pollution are hot-mix asphalt paving plants and asphalt-roofing manufacturing facilities. Particle-size distribution and degree of application of control information were not available for the asphalt-roofing manufacturing operations. As a result, fine-particle emissions were determined only for the hot-mix asphalt paving plants.

The major source of dust in hot-mix asphalt paving plants is the rotary dryer. However, while dust from the rotary dryer is the greatest source, dust emitted from the vibrating screens, bucket elevator, storage bins, and weight hopper is also significant. In some plants, the dryer dust problem is handled separately from the other sources. However, the trend is to combine both dryer and vent line sources (fugitive sources) together with a single collector fan system.

Fine-particle emissions were estimated for both the rotary dryer and the vent line sources as shown in Table 12. Calculations are summarized in Tables E-1 to E-10, pages 230 to 239. Emissions are estimated at 170,500 tons/year. This represents 85% of the total mass emission reported in

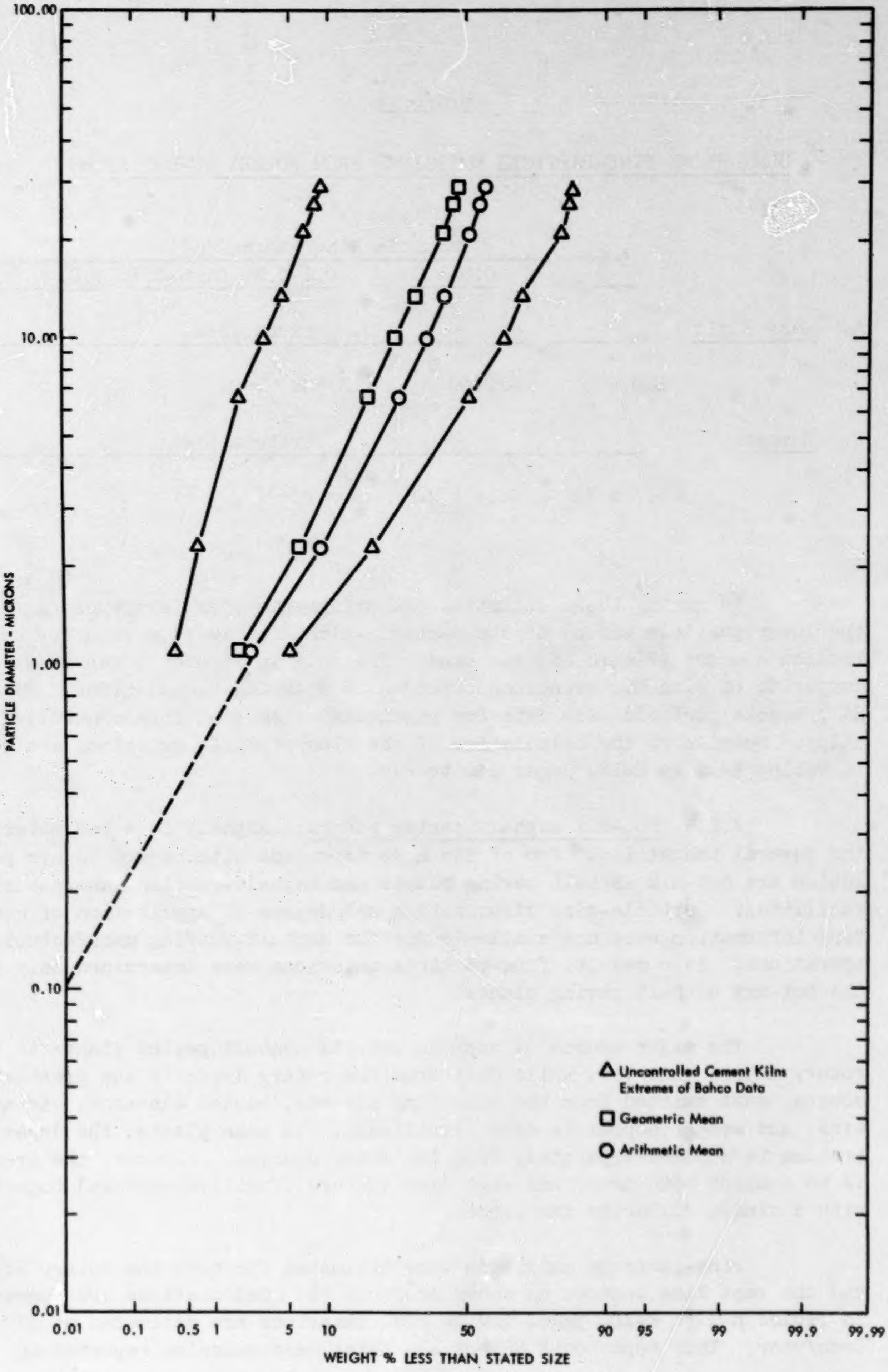

Figure 33 - Particle-Size Distributions of Particulates Emitted from Uncontrolled Cement Kilns

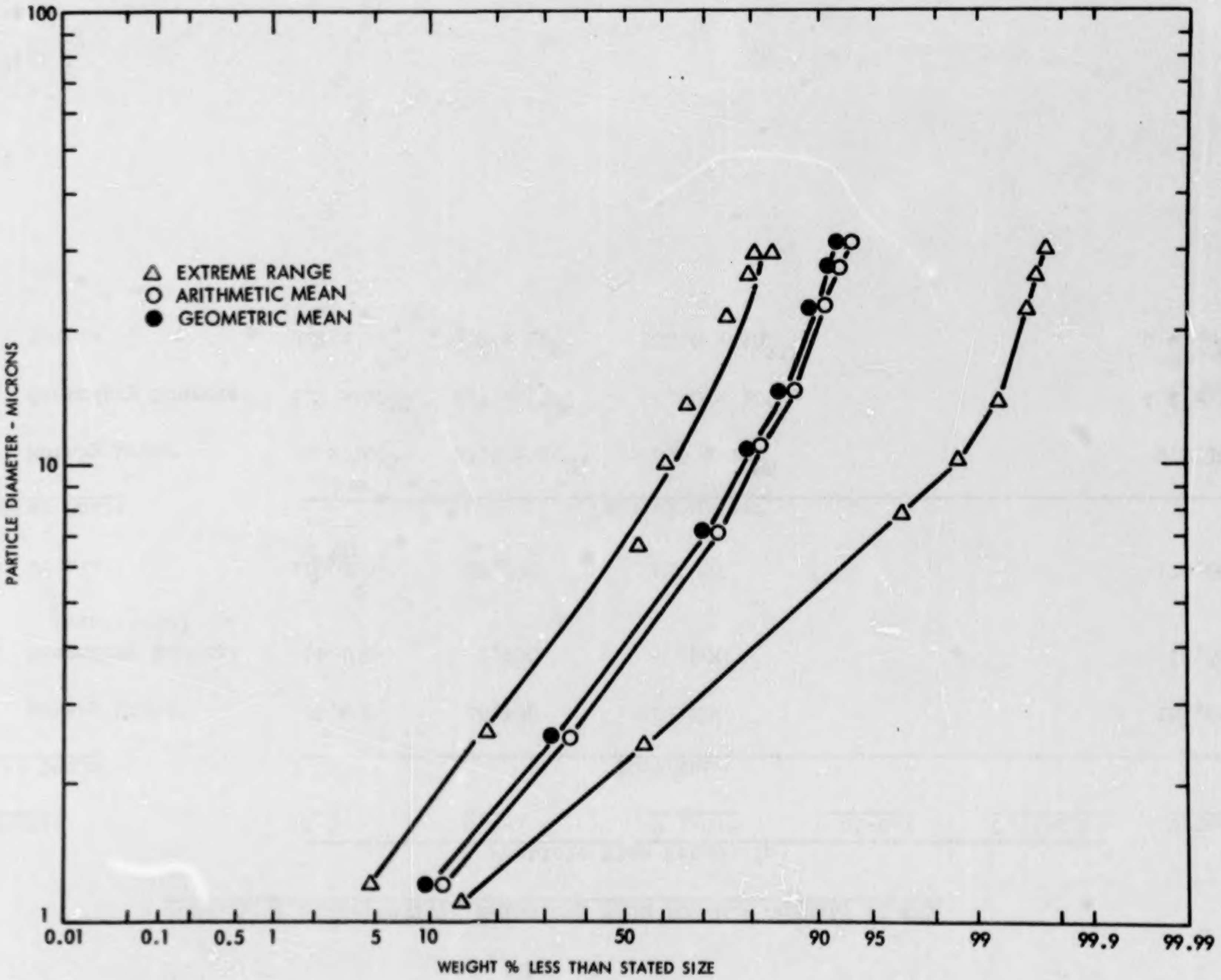

Figure 34 - Particle-Size Distributions of Particulates Emitted from Cement Kilns Controlled by Electrostatic Precipitators

TABLE 12

SUMMARY OF FINE-PARTICLE EMISSIONS FROM HOT-MIX ASPHALT PLANTS

Source	Particle Size Ranges (μ)					
	1-3	0.5-1	0.1-0.5	0.05-0.1	0.01-0.05	Total
A. Mass Basis	Tons/Year					
1. Rotary Dryer	96,400	36,300	21,500			154,200
2. Secondary Sources (vent line)	14,400	1,700	200			16,300
Totals	110,800	38,000	21,700			170,500
B. Number Basis	Particles/Year					
1. Rotary Dryer	8×10^{21}	57.5×10^{21}	5.3×10^{23}			6×10^{23}
2. Secondary Sources	1.2×10^{21}	2.7×10^{21}	4.95×10^{20}			4.4×10^{21}
Totals	9.2×10^{21}	60.2×10^{21}	530.5×10^{21}			6×10^{23}

Table 4.1-1, Volume I. Particle-size distributions for uncontrolled rotary dryers and vent lines are presented in Figures 35 and 36. The particle-size data in Figure 35 were obtained from 20 individual dryers, while those in Figure 36 were obtained from only two different vent lines.

7.2.7 Ferroalloy plants: The production of ferroalloys has many dust or fume producing steps. Materials handling, crushing and grinding operations generate coarse dust, while the pyrometallurgical steps release metallic fumes. Particle-size data were available only for the pyrometallurgical operations, and as a consequence, fine-particle emissions were estimated only for these operations.

Figure 37 presents available data on the particle-size distributions of fume emitted from uncontrolled ferroalloy electric furnaces. The data in Figure 37 were obtained for a furnace producing FeSi (50%), and are assumed to be representative for all ferroalloys produced in electric furnaces. Particle-size distributions from electric furnaces producing a variety of ferroalloy materials range from 0.05-1.0 μ (Table 17-4, Ref. 18), and, on this basis, the above assumption is justified.

Table 13 presents the estimates of emissions from ferroalloy production. Tables E-18 to E-21, pages 247 to 250, summarize calculations of fine-particle emissions from ferroalloy electric furnaces. Emissions are estimated to be 152,300 tons/year, which is approximately equal to the 150,000 tons/year reported for total mass emissions from these furnaces in Table 4.1-1, Volume I.

Emissions from ferroalloy blast furnaces were assumed to be negligible except for fugitive sources. About 80% of the dust from ferroalloy blast furnaces is < 1 μ.[18] If the total mass emissions of 1,000 tons/year listed in Table 4.1-1, Volume I, are assumed to be from fugitive sources, then about 800 tons/year of fine particulate are emitted from the blast furnace.

7.2.8 Lime plants: The major particulate emission source in lime plants is the rotary calcining kiln. Secondary sources include materials handling, crushing, and screening operations. Table 14 summarizes fine-particle emissions from lime plants. Individual sources are discussed in the following sections.

7.2.8.1 Rotary kilns: Calculations of the estimates of fine-particle emissions from rotary kilns are presented in Tables E-62 to E-67, pages 291 to 296. Emissions are estimated to be 87,800 tons/year, which is about 30% of the total mass emission reported for this source in Table 4.1-1, Volume I.

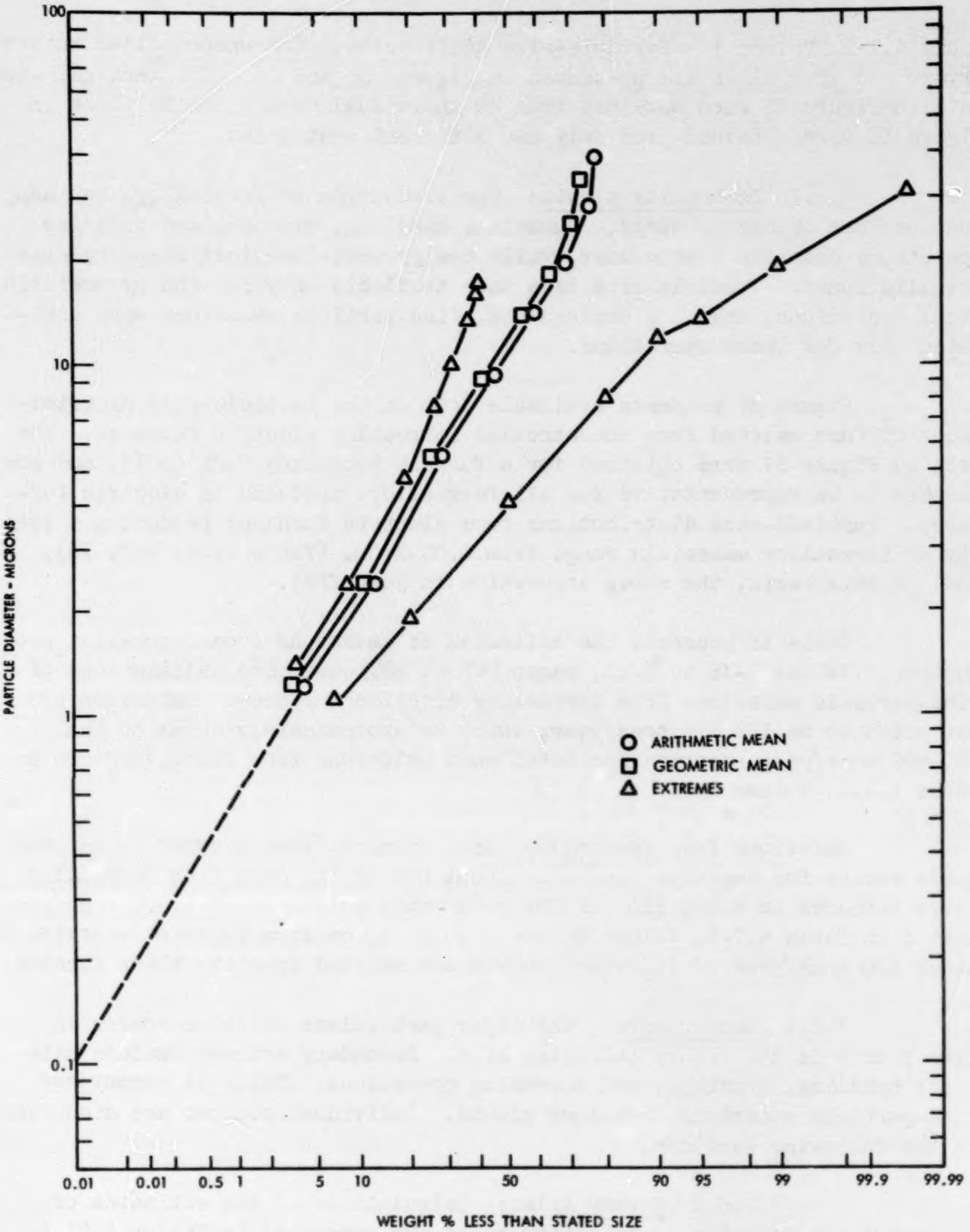

Figure 35 - Particle-Size Distribution of Particulates Emitted from Uncontrolled Hot-Mix Asphalt Plant Dryers (Bahco data)

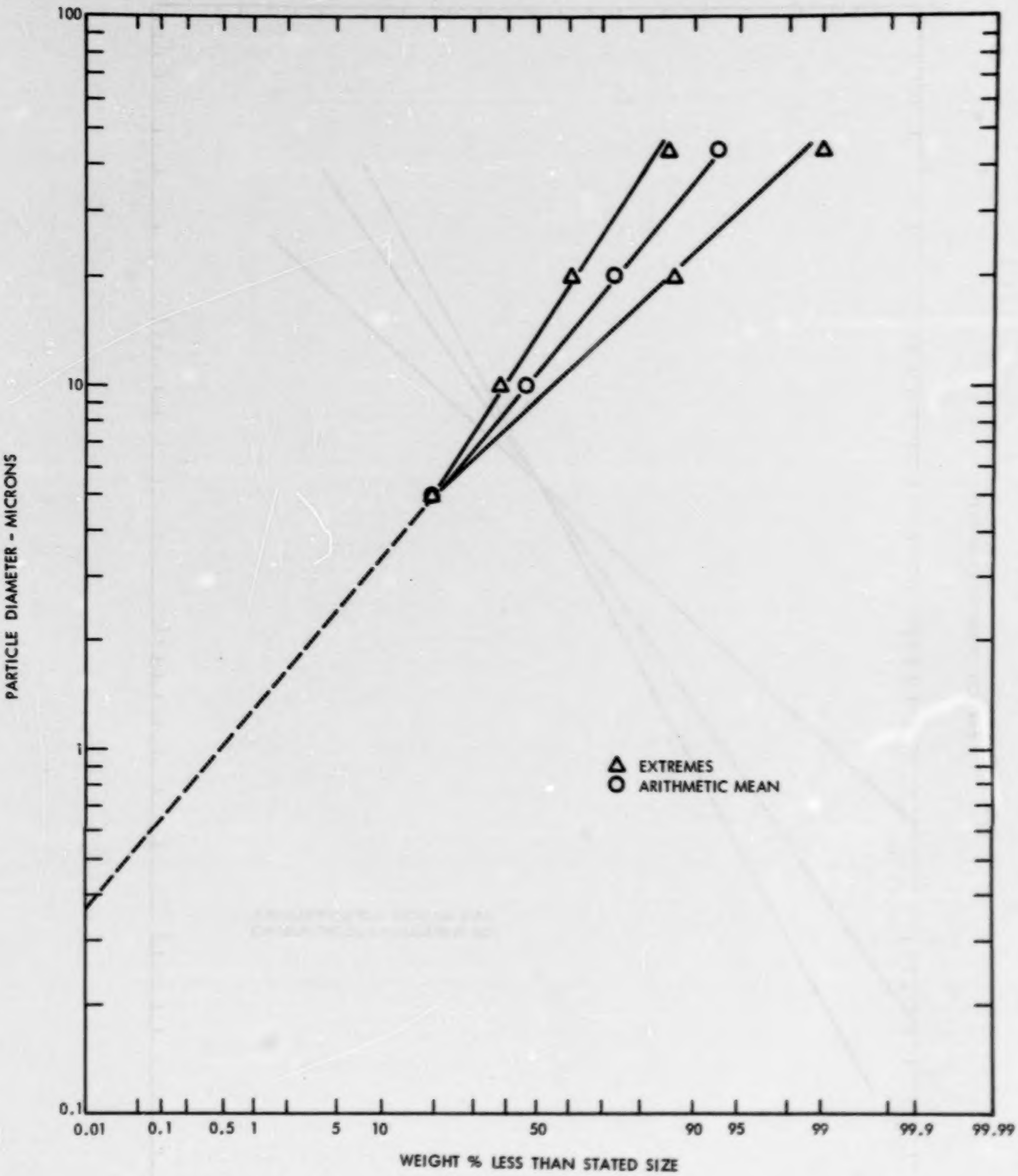

Figure 36 - Particle-Size Distribution of Particulates Emitted from Uncontrolled Hot-Mix Asphalt Plant Vent lines (Bahco data)

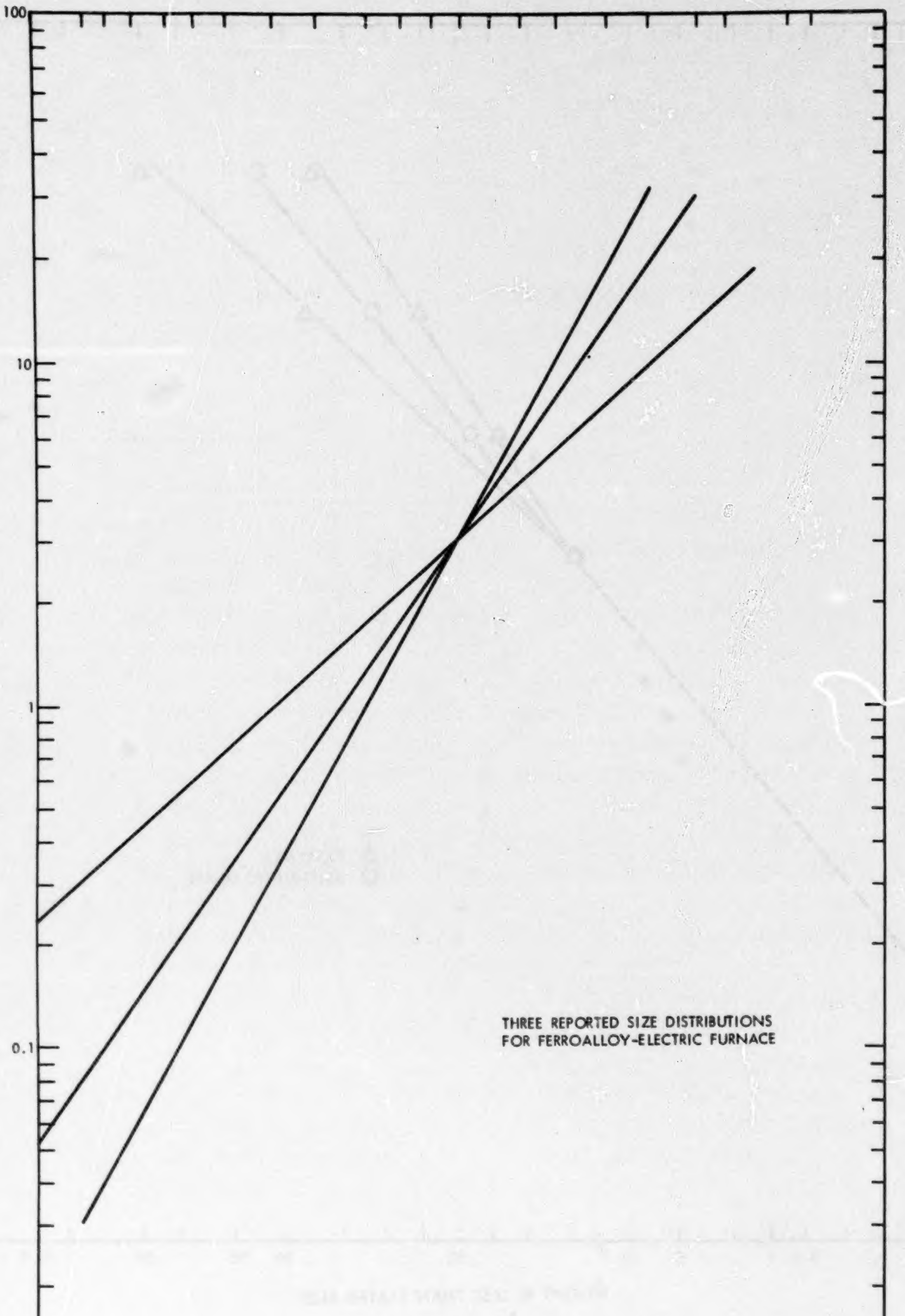

Figure 37 - Particle-Size Distributions of Particulates Emitted from Uncontrolled Ferroalloy Electric Furnaces[60] (optical technique)

TABLE 13

SUMMARY OF FINE-PARTICLE EMISSIONS FROM FERROALLOY PLANTS

Source	Particle Size Ranges (μ) 1-3	0.5-1	0.1-0.5	0.05-0.1	0.01-0.05	Total
A. Mass Basis	Tons/Year					
1. Electric Furnace	18,400	27,800	81,100	17,300	7,700	152,300
2. Blast Furnace	800					800
Totals	19,200	27,800	81,100	17,300	7,700	153,100
B. Number Basis	Particles/Year					
1. Electric Furnace	1.33×10^{21}	37×10^{21}	17.3×10^{23}	2.3×10^{25}	16.5×10^{25}	19×10^{25}
2. Blast Furnace	5.8×10^{19}					
Totals	1.4×10^{21}	37×10^{21}	17.3×10^{23}	2.3×10^{25}	16.5×10^{25}	19×10^{25}

TABLE 14

SUMMARY OF FINE-PARTICLE EMISSIONS FROM LIME PLANTS

	Particle Size Ranges (μ)					
Source	1-3	0.5-1	0.1-0.5	0.05-0.1	0.01-0.05	Total
A. Mass Basis	Tons/Year					
1. Rotary Kiln	40,600	18,800	23,600	3,000	1,800	87,800
2. Crushing and Screening	25,000-99,000*					25,000-99,000
Totals	65,600-139,600	18,800	23,600	3,000	1,800	112,800-186,800
B. Number Basis	Particles/Year					
1. Rotary Kiln	3.14×10^{21}	27.6×10^{21}	5.4×10^{23}	4.4×10^{24}	4.1×10^{25}	46×10^{24}
2. Crushing and Screening	$1.93\text{-}7.65 \times 10^{21}$					$1.93\text{-}7.65 \times 10^{21}$
Totals	$5.1\text{-}10.8 \times 10^{21}$	27.6×10^{21}	5.4×10^{23}	4.4×10^{24}	4.1×10^{25}	46×10^{24}

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* See Section 7.2.8.2 for discussion of calculation of fine-particle emissions.

Particle-size distribution data for uncontrolled kilns are shown in Figure 38. The data in Figure 38 were obtained from 19 individual kilns. Information on percentage application of control was obtained from the telephone survey reported in Section 5.7, Volume I.

The fine-particle emissions for rotary kilns controlled by cyclones and wet scrubbers were also determined by using particle-size distributions obtained from controlled rotary kilns (Figure 39). In Figure 39 the cyclone curve is the arithmetic average of 13 individual size analyses on different units, while the rotoclone, wet scrubber, and bypass stack curves represent only a single particle size analysis for each device. The cyclone outlet size distribution curve shows that 58 wt. % is $< 3\ \mu$. Assuming an overall efficiency of 70% for cyclones on rotary lime kilns, fine-particle emissions are estimated at

$$(261{,}000\ \text{tons/year})(1-0.70)(0.58) = 45{,}400\ \text{tons/year}$$

$< 3\ \mu$. This compares with 32,300 tons/year calculated from data in Figure 38 and the fractional efficiency curve for a medium-efficiency cyclone.

The wet scrubber outlet size distribution shows 67% $< 3\ \mu$. Assuming an overall efficiency of 90% for scrubbers on rotary lime kilns, fine-particle emissions are estimated at

$$(449{,}000\ \text{tons/year})(1-0.90)(0.67) = 30{,}100\ \text{tons/year}$$

$< 3\ \mu$. This compares with 25,900 tons/year calculated from data in Figure 38 and the fractional efficiency curve for a medium-efficiency wet scrubber.

Particle-size distribution data were not available for vertical lime kilns, and no estimate of fine-particle emissions was made for these units. However, total emissions from these kilns are only 4,000 tons/year (Table 4.1-1, Volume I), and exclusion of fine-particle emissions from these kilns is justified.

7.2.8.2 Crushing and screening: Gross estimates were made of the fine-particle emissions from the crushing and screening operations in lime plants by utilizing the particle-size data shown in Figures 40, 41 and 42. The size distributions for the screenhouse, hammermill and raymond mill indicate 46 wt. %, 30 wt. %, and 36 wt. % $< 3\ \mu$. The average is 37 wt. % $< 3\ \mu$. Total process emissions for the crushing and screening

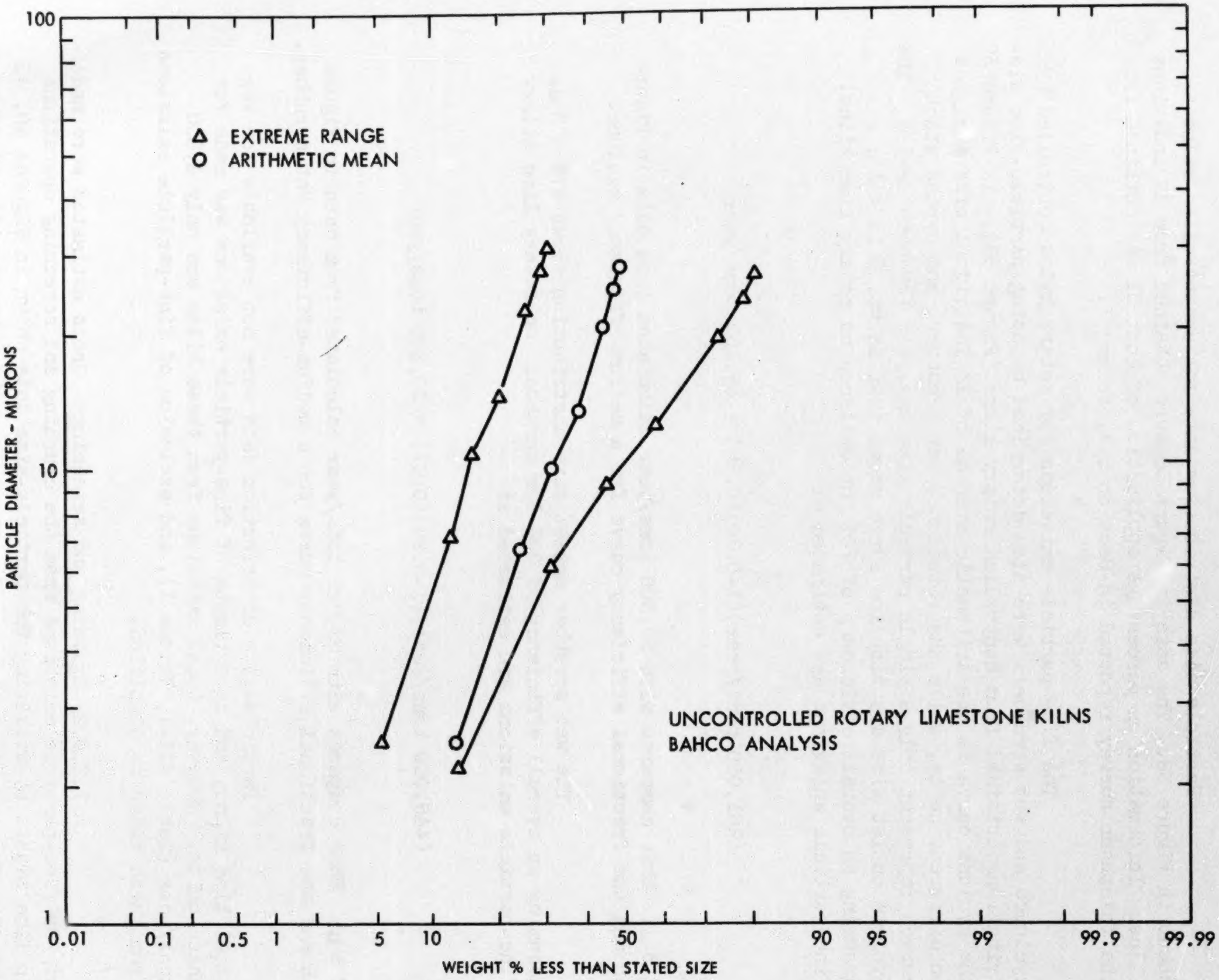

Figure 38 - Particle-Size Distributions of Particulates Emitted from Uncontrolled Rotary Limestone Kilns

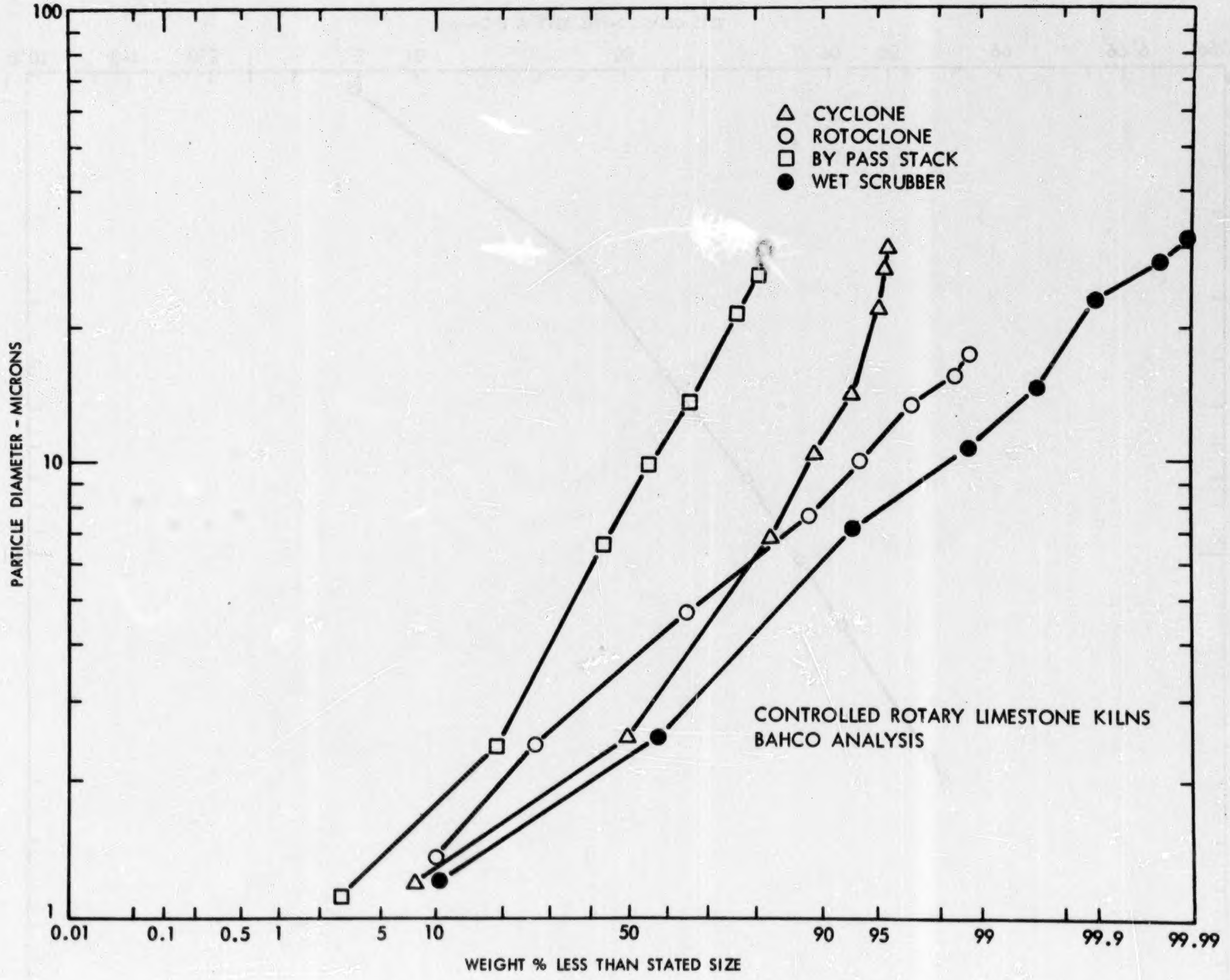

Figure 39 - Particle-Size Distributions of Particulates Emitted from Controlled Limestone Kilns

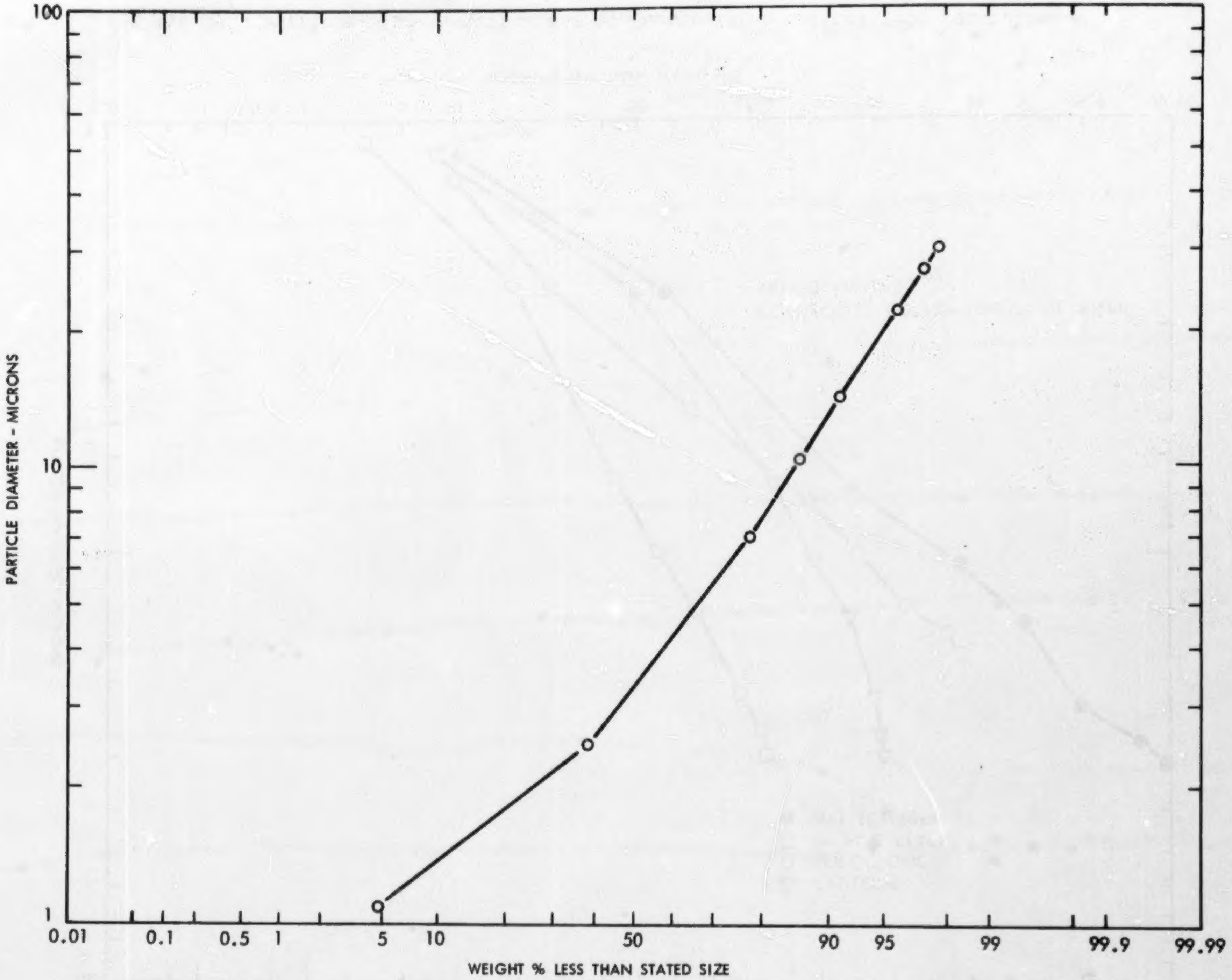

Figure 40 - Particle-Size Distribution of Particulates Emitted from Uncontrolled Lime and Limestone Screenhouses (Bahco data)

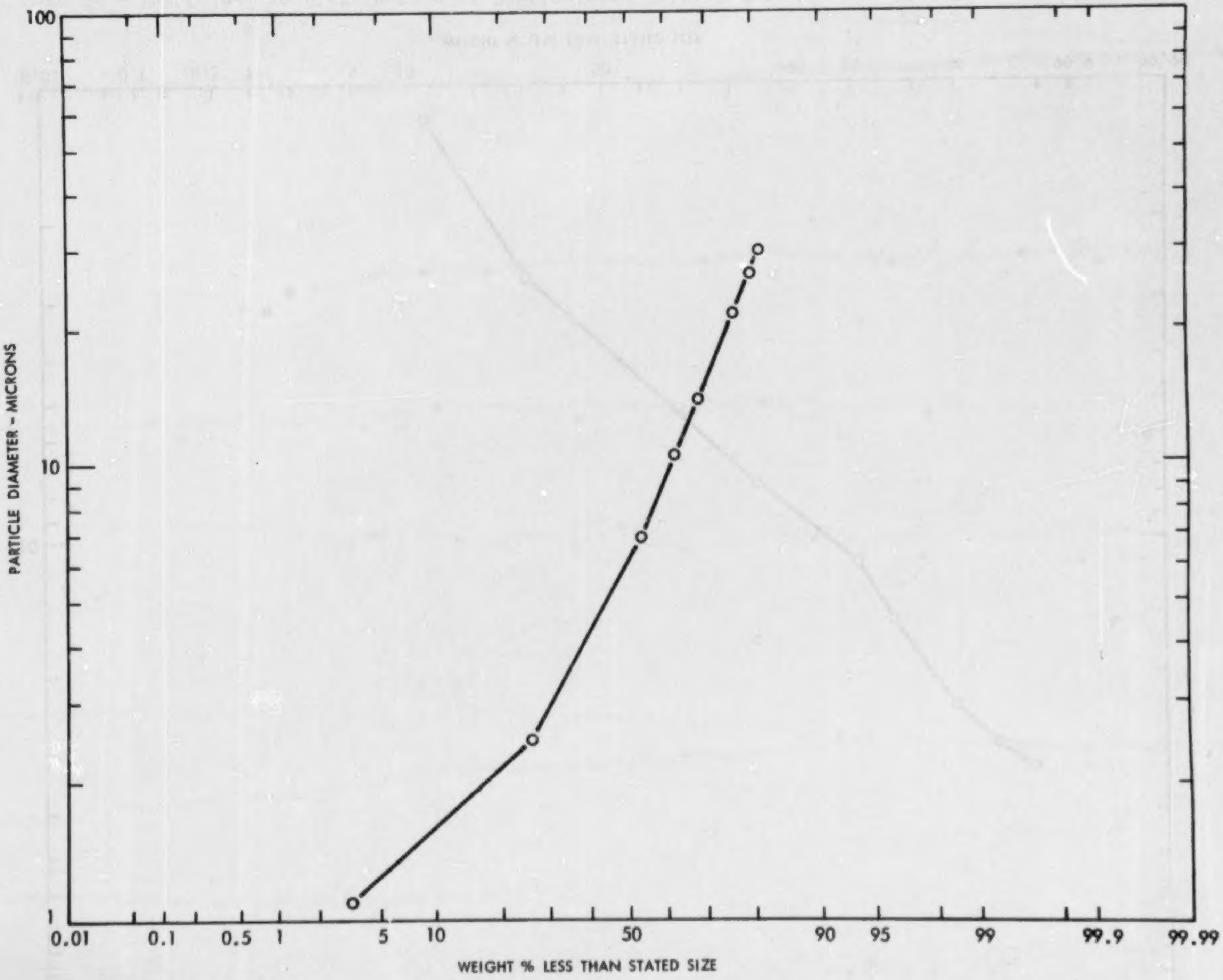

Figure 41 - Particle-Size Distribution of Particulates Emitted from Uncontrolled Lime and Limestone Hammermills (Bahco data)

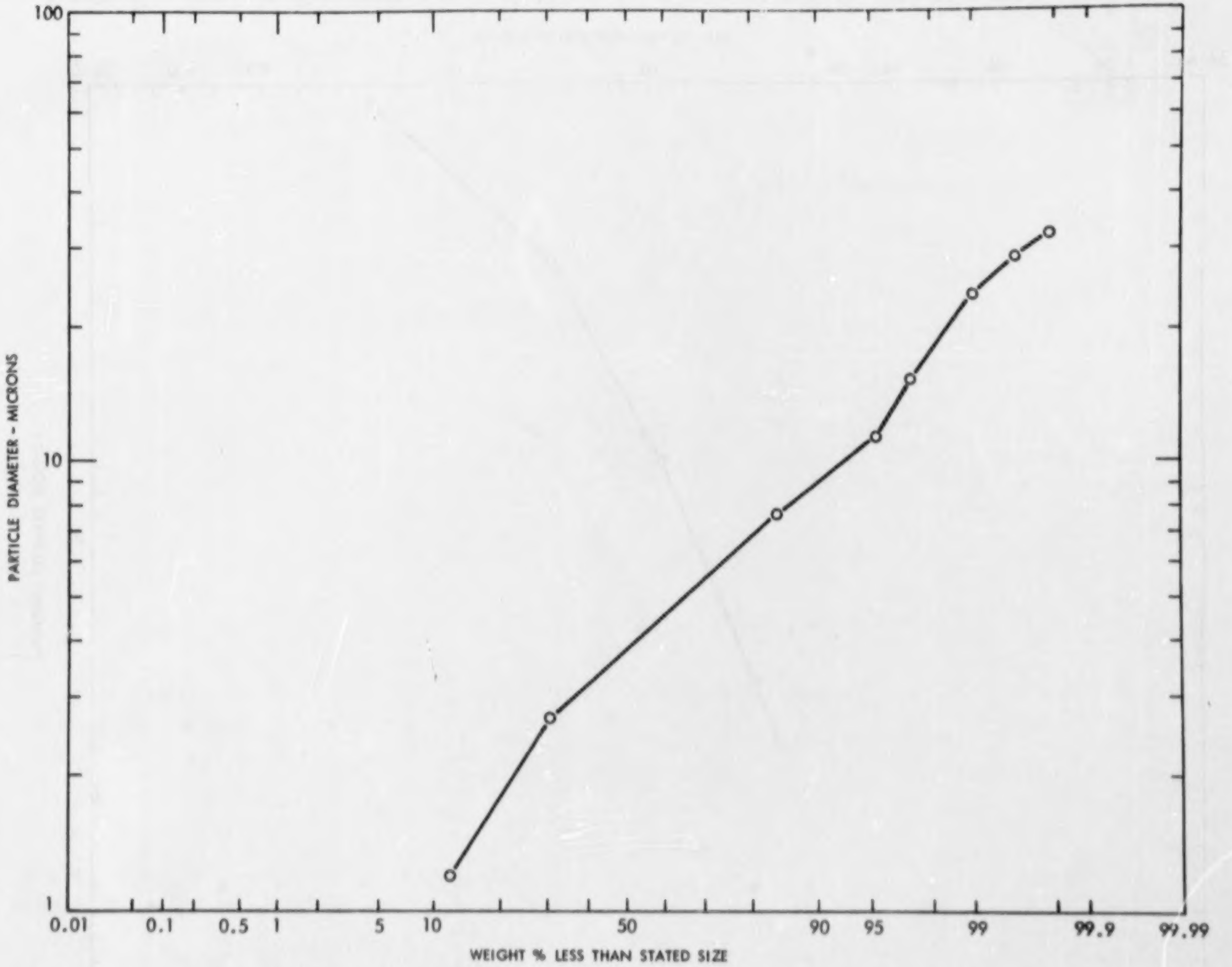

Figure 42 - Particle-Size Distribution of Particulates Emitted from Uncontrolled Lime and Limestone Raymond Mills (Bahco data)

operations are 336,000 tons/year (Table 4.8-1, Volume I). If the net control is 20%, the emissions $< 3\ \mu$ are estimated to be

$$(336{,}000 \text{ tons/year})(1-0.20)(0.37) = 99{,}000 \text{ tons/year} \quad .$$

However, this number may be erroneous because the limited information on control procedures for these sources obtained during the survey of the lime industry indicated that many of these sources are controlled with fabric filters. Therefore, net control of these sources may be closer to 80% and the fine-particle emissions about 25,000 tons/year.

7.2.9 Secondary nonferrous metallurgy: Particle-size distributions from either uncontrolled or controlled sources are meager for all processes in secondary nonferrous metallurgy. Information on degree of application of control is also meager for all sources. Available particle-size data for all the specific sources listed under the secondary nonferrous metallurgy category in Table 4.1-1, Volume I, indicate that uncontrolled sources emit nearly 100% $< 2\ \mu$.[18] Therefore, a gross estimate of fine-particle emissions from secondary nonferrous metallurgical operations is 127,000 tons/year. The number of particles emitted that are $< 2\ \mu$ in diameter is estimated to be 7.85×10^{21} particles/year.

7.2.10 Carbon black: The particle size of carbon black particles is 0.01-0.4 μ in diameter.[18] Therefore, the total mass emissions (93,000 tons/year) listed in Table 4.1-1, Volume I, are also the fine-particle emissions. The number of particles emitted that are $< 2\ \mu$ in diameter is estimated to be 1×10^{22} particles/year.

7.2.11 Coal preparation plants: Thermal dryers are the only particulate emission source in coal preparation plants for which adequate data were available to permit an estimate of fine-particle emissions. The fine-particle emissions from thermal dryers were calculated using an emissions factor of 12 lb/ton following the primary cyclones, and available extent of control information.[1] Information on control of thermal dryers indicates that all plants are equipped with primary cyclones, and that 85% of the production is also equipped with wet scrubbers following the primary cyclones. The available particle-size data for thermal dryer effluents shown in Figure 43 indicate that the particles exiting the primary cyclone average about 40% $< 3\ \mu$.

Using the emission factor of 12 lb/ton, the total particulate emitted from the primary cyclones was calculated to be 438,000 tons/year. Since 15% of the production is not equipped with additional control devices, the total emissions from these units were calculated to be 65,700 tons/year with 40% of the quantity, or 26,300 tons/year, being $< 3\ \mu$.

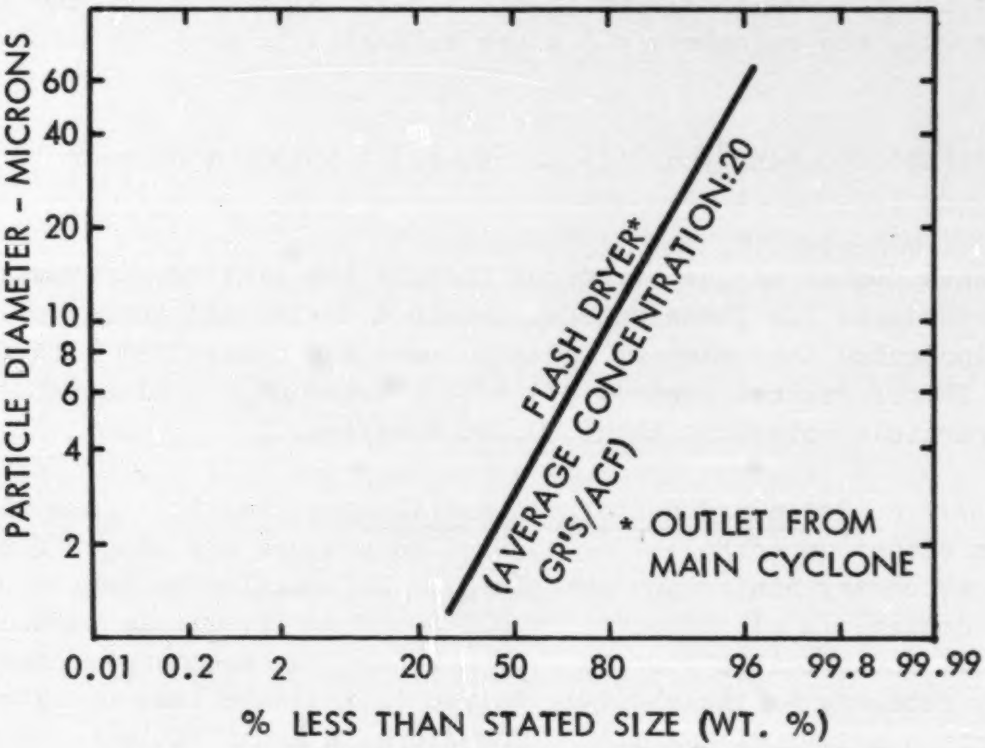

Figure 43 - Particle-Size Analysis for Particulates Emitted from Coal Thermal Dryers[18]

The remaining 85% of the production, which accounts for 372,300 tons/year emissions from the primary cyclones, is controlled with wet scrubbers. Assuming that the wet scrubbers are "medium" efficiency scrubbers, and that the penetration for < 3 μ particles was 25%, fine-particle emissions were calculated to be 37,200 tons/year. Therefore, the total fine-particle emissions from thermal dryers are:

Plants controlled with cyclones = 26,300 tons/year < 3 μ
Plants controlled with cyclones and scrubbers = 37,200 tons/year < 3 μ

Total fine-particle emissions = 63,500 tons/year < 3 μ

The 63,500 tons/year represent 67.5% of the total mass emission for thermal dryers reported in Table 4.1-1, Volume I.

The number of particles emitted that are < 3 μ in diameter is estimated to be 3.9×10^{21} particles/year.

7.2.12 Petroleum refineries: Catalyst regenerators, boilers, process heaters, decoking operations, and incinerators are sources of particulate pollution. Meager particle-size data exist for all uncontrolled sources, and only an estimate of fine-particle emissions from catalyst regenerators was made.

Figure 44 summarizes available particle-size distribution data from eight uncontrolled FCC units. In order to use this particle-size data to calculate fine-particle emissions, it is necessary to know the quantity entering the cyclones. The total mass emissions of 45,000 tons/year from FCC units (Table 4.1-1, Volume I) was calculated on the basis of an emission factor for controlled FCC units. Assuming that all FCC units are equipped with 80% efficiency cyclones, the quantity of particulate material entering the cyclones is 225,000 tons/year.

Using the inlet rate of 225,000 tons/year, the particle-size data in Figure 44, and the fractional efficiency curve for a high efficiency cyclone (Figure 17), fine-particle emissions were calculated to be 56,600 tons/year. This figure exceeds the total mass emission of 45,000 tons/year. However, in view of the assumptions in the calculations, the difference in the emissions is not considered significant, and fine-particle emissions are assumed to equal the total mass emissions of 45,000 tons/year.

The number of particles emitted that are $< 2\ \mu$ in diameter is estimated to be 3.7×10^{21} particles/year.

7.2.13 Fertilizer and phosphate rock: Particulate emissions from the processing of phosphate rock and from fertilizer manufacturing originate from dryers, roasters, digesters, granulators, and coolers. Particle-size distributions were obtained only for granulators and dryers used in the manufacture of phosphate fertilizers. Figure 45 presents the particle-size data for these sources. The data were obtained from eight individual fertilizer plants.

Because of the lack of adequate particle-size distribution data for the other sources, estimates of fine-particle emissions were made only for the granulators and dryers. Fine-particle emissions from the granulators and dryers are estimated to be 13,700 tons/year as shown in Table 15. Details of the calculations are given in Tables E-22 to E-25, pages 251 to 254. This represents about 8% of the total mass emissions reported for these sources in Table 4.1-1, Volume I.

7.2.14 Iron foundries: The iron melting process in foundries is the principal source of particulate emissions. Cupola, electric arc, electric induction, and reverberatory air furnaces are used to obtain the molten metal. Secondary sources of particulates include materials handling, casting shakeout systems, buffing and grinding operations, and core ovens.

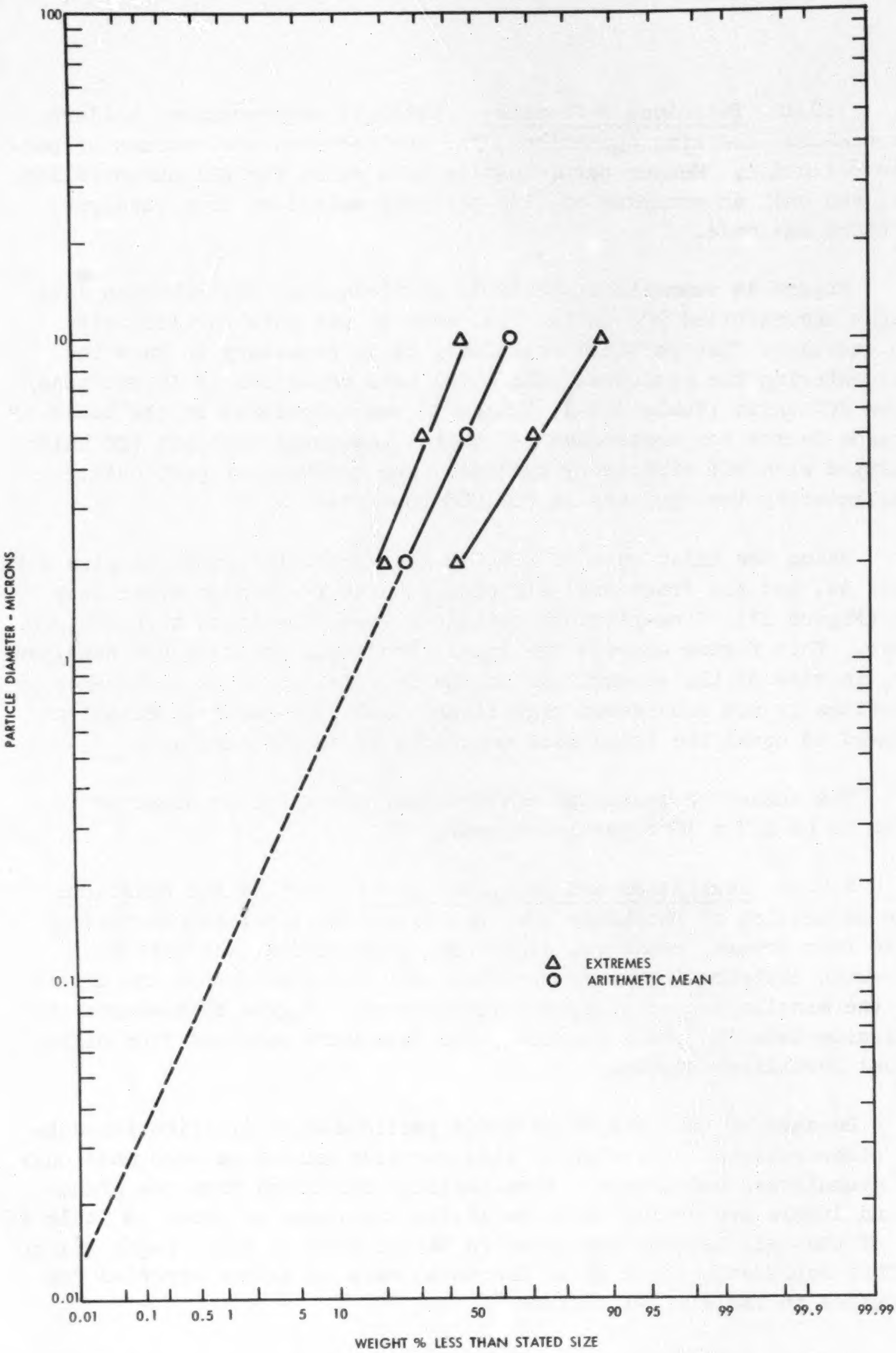

Figure 44 - Particle-Size Distribution of Particulates Emitted from Petroleum FCC Units (cyclone inlet, Bahco data)

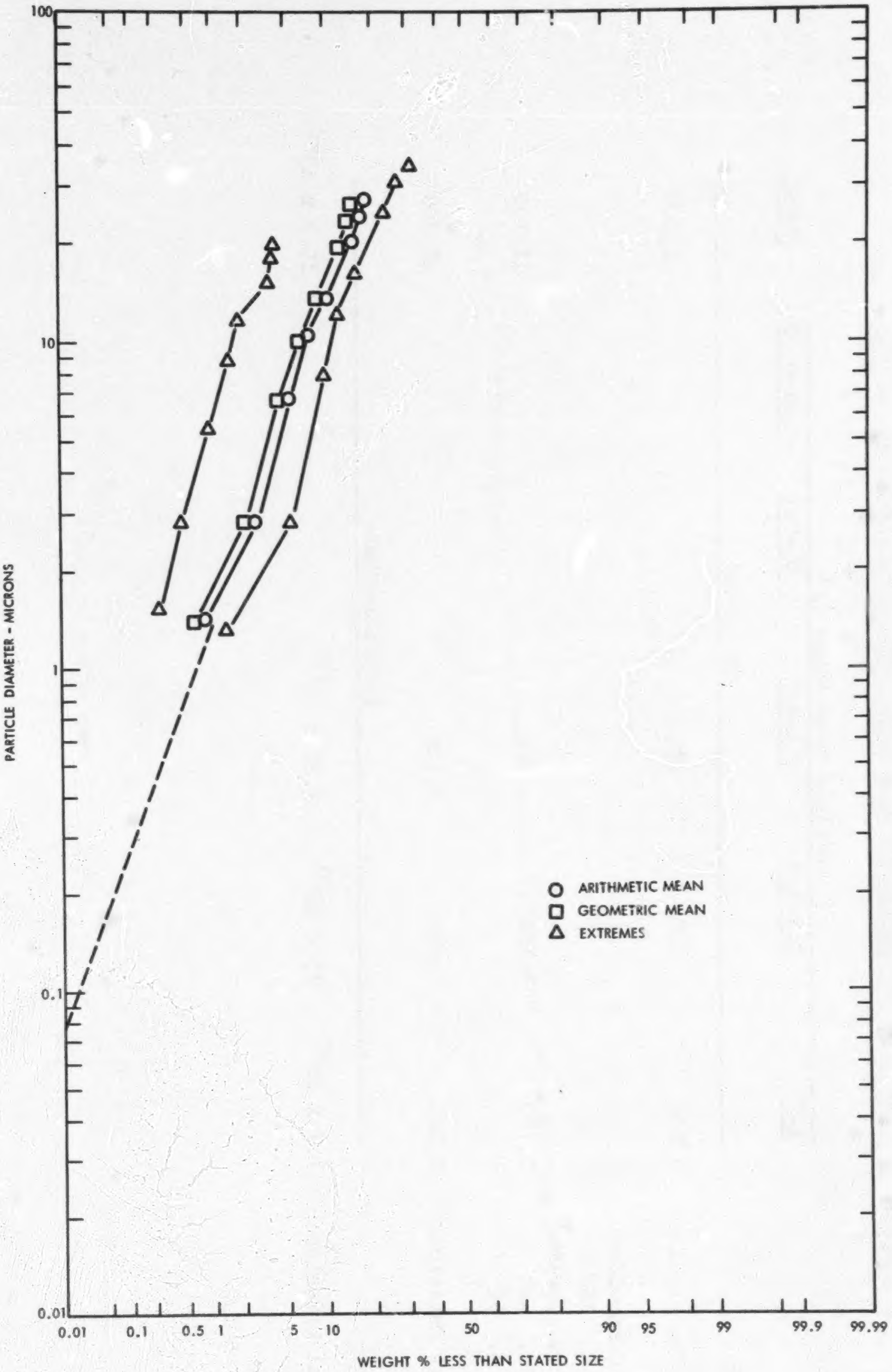

Figure 45 - Particle-Size Distribution of Particulates Emitted from Uncontrolled Fertilizer Dryers (Bahco data)

TABLE 15

SUMMARY OF FINE-PARTICLE EMISSIONS FROM FERTILIZER GRANULATORS AND DRYERS

	Particle Size Range (μ)					
	1-3	0.5-1.0	0.1-0.5	0.05-0.1	0.01-0.05	Total
A. Mass	Tons/Year					
1. Uncontrolled	1,400	400	200			2,000
2. Controlled						
a. ESP						
b. Cyclone						
c. Wet	5,700	3,100	2,900			11,700
d. FF						
Total Emissions	7,100	3,500	3,100			13,700
B. Number	Particles/Year					
Total Emissions	7.7×10^{20}	72×10^{20}	9.95×10^{22}			10.7×10^{22}

Particle-size distributions, emission factors, and degree of application of control information were available only for the cupola furnaces, and estimates of fine-particle emissions were confined to that source.

Table 16 summarizes fine-particle emissions from cupolas. Details of the calculations are given in Tables E-44 to E-49, pages 273 to 278. The 13,100 tons/year of fine particulate matter comprises approximately 12.5% of the total mass emission from these furnaces (Table 4.1-1, Volume I). Available particle-size data for uncontrolled cupolas are presented in Figure 46. The data in Figure 46 were obtained from 25 individual cupola

7.2.15 Acids:

7.2.15.1 Sulfuric acid: Chamber plants are uncontrolled, and the particles emitted from these plants are typically 90-96% < 3 μ.[8] Total mass emissions from chamber plants are only 2,000 tons/year. Fine-particle emissions are estimated to be 5% of this total, or 100 tons/year.

The available particle-size data for effluents from contact plants show that 65 wt. % are < 3 μ. Since the control devices normally remove mostly larger particles, it is estimated that at least 65 wt. % of the total emissions of 4,000 tons/year, or 2,600 tons/year, are < 3 μ.

Fine-particle emissions from spent acid concentrators were not estimated because of inadequate particle-size data. The number of particles emitted from sulfuric acid plants that are < 3 μ in diameter is estimated to be 3.4×10^{20} particles/year.

7.2.15.2 Phosphoric acid--thermal process: Particle-size data for thermal-process phosphoric acid plants indicate that particulate effluents are 50 wt. % < 1.6 μ. The only estimate of fine-particle emissions that can be made is that at least 50% of the total emissions of 2,000 tons/year, or 1,000 tons/year, are < 1.6 μ.

The number of particles emitted that are < 3 μ in diameter is estimated to be 1.2×10^{20} particles/year.

7.2.16 Primary nonferrous metallurgy:

No estimate was made for fine-particle emissions from primary nonferrous metallurgy sources. Very little particle-size data are available for the many varied sources within each of the primary nonferrous groups. These sources range from copper reverberatory furnaces (51% < 37 μ) to zinc sintering machines (100% < 10 μ). The variability of the operations and the inadequate particle-size data do not permit even a generalization as to percent < 2 μ.

Furthermore, the extent of control information for the many primary nonferrous operations has only fair reliability, and this would further decrease the accuracy of any estimation of fine-particle emissions.

TABLE 16

SUMMARY OF FINE-PARTICLE EMISSIONS FROM IRON FOUNDRY CUPOLAS

	Particle Size Range (μ)					
	1-3	0.5-1.0	0.1-0.5	0.05-0.1	0.01-0.05	Total
A. Mass	Tons/Year					
1. Uncontrolled	5,800	1,900	2,200	300	300	10,500
2. Controlled						
a. ESP						
b. Cyclone	300	100	200			600
c. Scrubber	700	400	700	100	100	2,000
d. FF						
Total Emissions	6,800	2,400	3,100	400	400	13,100
B. Number	Particles/Year					
Total Emissions	5.25×10^{20}	35.3×10^{20}	7.1×10^{22}	5.9×10^{23}	9.2×10^{24}	9.9×10^{24}

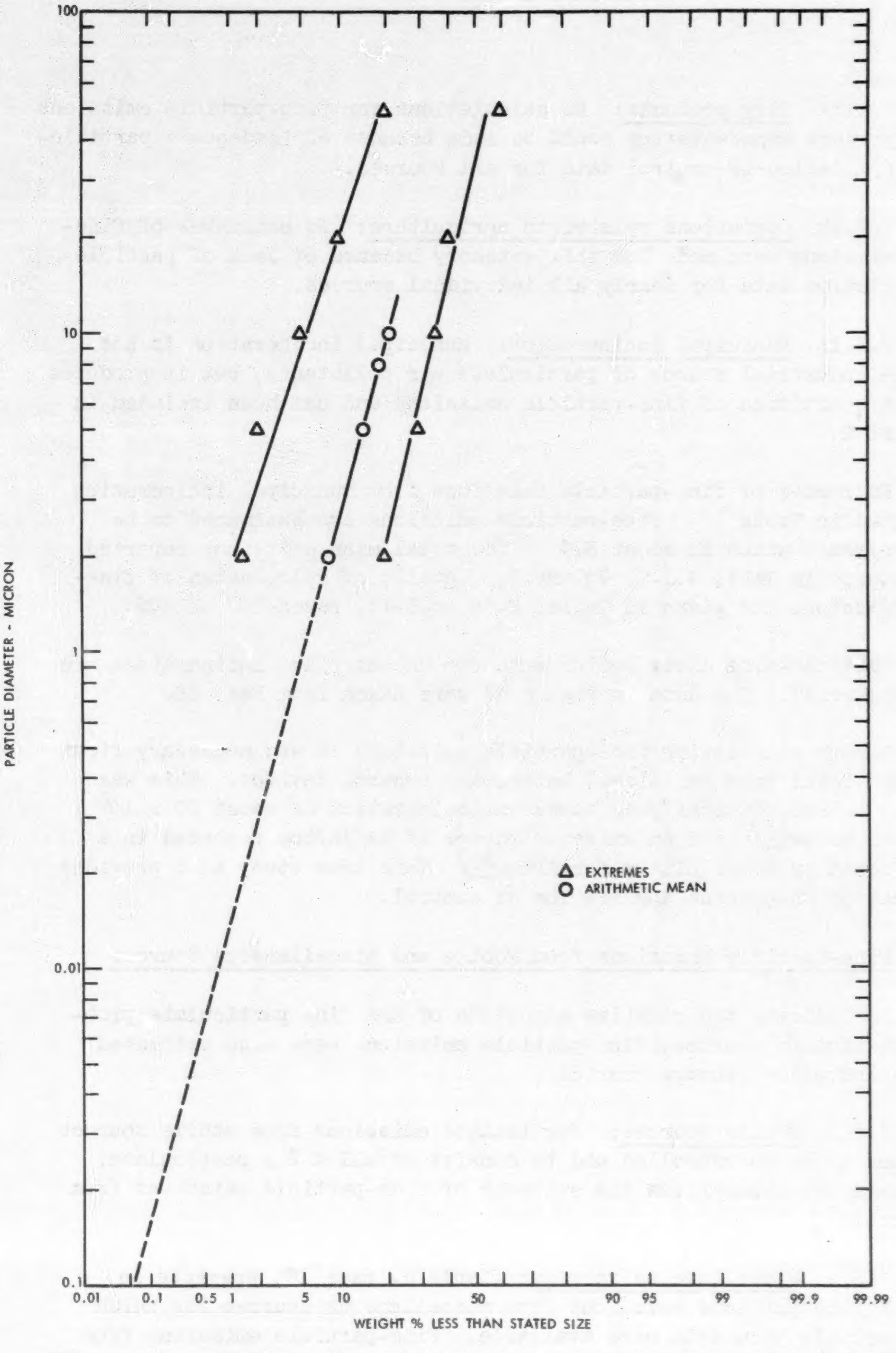

Figure 46 - Particle-Size Distribution of Particulates Emitted from Uncontrolled Iron Foundry Cupolas (Bahco data)

7.2.17 Clay products: No calculations for fine-particle emissions from clay product manufacturing could be made because of inadequate particle-size and application-of-control data for all sources.

7.2.18 Operations related to agriculture: No estimates of fine-particle emissions were made for this category because of lack of particle-size distribution data for nearly all individual sources.

7.2.19 Municipal incineration: Municipal incineration is not strictly an industrial source of particulate air pollutants, but it produces significant quantities of fine-particle emissions and has been included in Tables 1 and 2.

Estimates of fine-particle emissions from municipal incineration are presented in Table 17. Fine-particle emissions are estimated to be 36,400 tons/year, which is about 37% of the total mass emissions reported for this source in Table 4.1-2, Volume I. Details of calculation of fine-particle emissions are given in Tables E-68 to E-73, pages 297 to 302.

Particle-size distribution data for uncontrolled incinerators are shown in Figure 47. The data in Figure 47 were taken from Ref. 18.

Before calculating fine-particle emissions it was necessary first to calculate total mass emissions, before any control devices. This was computed to be 240,000 tons/year based on incineration of about 20 x 10^6 tons/year of waste[31] and an emission factor of 24 lb/ton reported in a study conducted by A. D. Little for APCO.[32] This same study also provided the information on percent application of control.

7.3 Fine-Particle Emissions from Mobile and Miscellaneous Sources

To indicate the relative magnitude of the fine particulate problem from stationary sources, fine-particle emissions were also estimated for mobile and miscellaneous sources.

7.3.1 Mobile sources: Particulate emissions from mobile sources were assumed to be uncontrolled and to consist of all $< 2\ \mu$ particulate. Table 4, page 10, summarizes the estimate of fine-particle emissions from these sources.

7.3.2 Miscellaneous sources: Table 5, page 10, presents an estimate of fine-particle emissions from miscellaneous sources for which adequate particle size data were available. Fine-particle emissions from natural dusts, forest fires, and agricultural burning could not be estimated because of lack of reliable particle size data.

TABLE 17

SUMMARY OF FINE-PARTICLE EMISSIONS FROM MUNICIPAL INCINERATORS

	Particle Size Range (μ)					
	1-3	0.5-1.0	0.1-0.5	0.05-0.1	0.01-0.05	Total
A. Mass	Tons/Year					
1. Uncontrolled	6,700	3,400	5,000	1,400	1,700	18,200
2. Controlled						
a. ESP						
b. Cyclone	1,100	700	1,100	300	400	3,600
c. Wet Scrubber	2,400	2,400	5,000	1,600	2,000	13,400
	200	200	400	200	200	1,200
Total Emissions	10,400	6,700	11,500	3,500	4,300	36,400
B. Number	Particles/Year					
Total Emissions	9×10^{20}	11×10^{21}	3×10^{23}	5.8×10^{24}	11×10^{25}	16.8×10^{25}

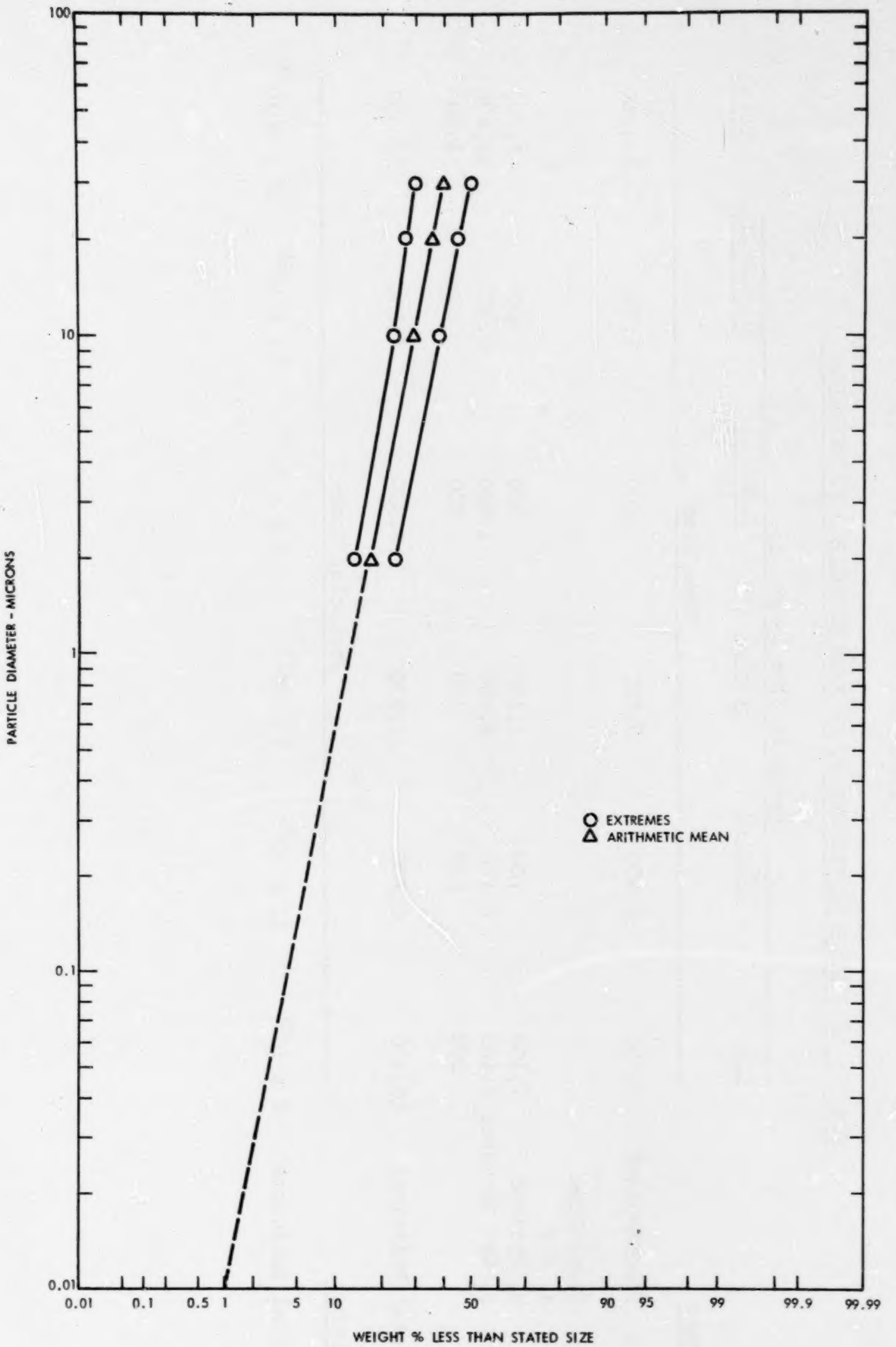

Figure 47 - Particle-Size Distribution of Particulates Emitted from Uncontrolled Municipal Incinerators (Bahco data)

8. Projections of Fine-Particulate Emissions to the Year 2000

8.1 Mass Basis

Projections of fine-particle emissions through the year 2000 were performed for those sources for which adequate particle-size distribution data and information on application of control devices were available. Two projection methods were used which are similar to Method 1 and Method 5 previously described in Volume I. The first method reflects no change in control, while the other method reflects establishment of controls on all sources by 1980 and an increasing use of the most efficient control devices.

Method 1 - The projection of emissions by Method 1 assumes that there will be no change in the net control for a source. This means that the emissions increase in proportion to increases in production capacity. Production figures were projected by the same methods outlined in Volume I, and were used to proportionally increase the current mass of fine-particle emissions. An example of the calculation method is given in Table 18.

TABLE 18

PROJECTIONS OF FINE-PARTICLE EMISSIONS FOR ASPHALT DRYERS
(Method 1)

Year	Production 10^6 Tons/Year	Production Ratio	Fine Particle Emissions (tons/year)
1968	251	1.00	154,200
1970	274	1.09	168,100
1975	333	1.33	205,100
1980	406	1.62	249,800
1985	498	1.98	305,300
1990	610	2.43	374,700
1995	747	2.98	459,500
2000	915	3.65	562,800

Method 2 - The projection of emissions by Method 2 also takes into account the increases in production, but two assumptions are also made:

1. All sources will be controlled by 1980; i.e., application of control will reach 100% by 1980.

2. Increased utilization of the most efficient control devices will continuously increase the efficiency of control on fine particles so that by the year 2000 it will be equivalent to controlling all sources with baghouses.

The fabric filter was selected as a reference standard of performance because it is one of the most efficient devices available today for collecting fine particulates. It seems realistic to assume that improvements in the other control devices and possible development of new devices would allow the efficiency of control, in the year 2000, to match the performance capability of the best devices that are presently available.

The calculation of projected fine-particle emissions by Method 2 uses the present average efficiency of control on fine particles as a starting point. Therefore, the first step in this method is the back calculation of the average efficiency of control on fine particles as shown in the example for asphalt dryers, Table 19.

TABLE 19

CALCULATION OF AVERAGE EFFICIENCY OF CONTROL FOR FINE PARTICLES FROM ASPHALT DRYERS
(Method 2)

1968 Total Production = 251 x 10^6 tons/year
Emission Factor = 32 lb/ton
Process Emissions = $15.5\% < 3\ \mu$
Fine Particle Emissions = 154,200 tons/year
Application of Control = 99%
Calculation of Average Efficiency of Control for Fine Particles (x):

$$(251 \times 10^6)\left(\frac{32}{2000}\right)(15.5\%)(1 - 0.99x) = 154{,}200$$

$$1 - 0.99x = 0.248$$

$$0.99x = 0.752$$

$$x = 0.76$$

Average Efficiency of Control for Fine Particles from Asphalt Dryers = 76%

The second step in the calculations is to determine the efficiency of control on fine particles using a baghouse. This is based on the particle-size distribution of the process emissions and the fractional efficiency curve for a fabric filter as shown in Table 20. The value computed is assumed to represent the efficiency of control for the source in the year 2000. The efficiency of control for the intervening years is increased linearly from the present value to the efficiency calculated for the year 2000.

TABLE 20

CALCULATION OF AVERAGE EFFICIENCY OF CONTROL ON FINE PARTICLES FOR FABRIC FILTER ON ASPHALT DRYER

Basis: 100 lb. of process emission

$15.5\% < 3\ \mu$

Fine Particle Process Emission - 15.5 lb.

Size Range (μ)	%	Fabric Filter Penetration (%)	Fine Particle Emission
1-3	12.6	0.5	0.06
0.5-1.0	2.18	1.8	0.04
0.1-0.5	0.71	3.3	0.02
			0.12

Average Efficiency of Fabric Filter on Fine Particles $= \frac{15.5 - 0.12}{15.5} = 99.2\%$

Method 2 also assumes that the application of control increases linearly to 100% by 1980, as shown in Table 21. Table 21 also summarizes the variables used to calculate the projected emissions of fine particles for asphalt dryers. The calculation of the projected fine-particle emissions for asphalt dryers is illustrated in Table 22.

TABLE 21

VALUES USED IN CALCULATION OF PROJECTED FINE-PARTICLE EMISSIONS FOR ASPHALT DRYERS

(Method 2)

At Present, Application of Control = 99%
Efficiency of Control on Fine Particles = 76%

Year	Production (tons/year)	Application of Control (%)	Fine-Particle Efficiency of Control (%)
1968	251×10^6	99	76
1970	274×10^6	99.1	77.5
1975	333×10^6	99.6	81.2
1980	406×10^6	100	84.9
1985	498×10^6	100	88.6
1990	610×10^6	100	92.3
1995	747×10^6	100	96.0
2000	915×10^6	100	99.2

TABLE 22

PROJECTIONS OF FINE-PARTICLE EMISSIONS FOR ASPHALT DRYERS

(Method 2)

Year	Calculation
1968	$(251 \times 10^6)\left(\frac{32}{2000}\right)(0.155)[1 - (0.99)(0.76)] = 154{,}200$ tons/year
1970	$(274 \times 10^6)\left(\frac{32}{2000}\right)(0.155)[1 - (0.991)(0.775)] = 157{,}600$ tons/year
1975	$(333 \times 10^6)\left(\frac{32}{2000}\right)(0.155)[1 - (0.996)(0.812)] = 157{,}700$ tons/year
1980	$(406 \times 10^6)\left(\frac{32}{2000}\right)(0.155)(1 - 0.849) = 152{,}000$ tons/year
1985	$(498 \times 10^6)\left(\frac{32}{2000}\right)(0.155)(1 - 0.886) = 140{,}800$ tons/year
1990	$(610 \times 10^6)\left(\frac{32}{2000}\right)(0.155)(1 - 0.923) = 116{,}500$ tons/year
1995	$(747 \times 10^6)\left(\frac{32}{2000}\right)(0.155)(1 - 0.960) = 74{,}100$ tons/year
2000	$(915 \times 10^6)\left(\frac{32}{2000}\right)(0.155)(1 - 0.992) = 18{,}200$ tons/year

Table 6, p. 13, and Figures 48 to 65 summarize the projections of fine-particle emissions on a mass basis. Fine-particle emissions for the sources listed in Table 6 can be reduced from 3.5×10^6 tons/year (1968 emission level) to 3.5×10^5 tons/year by the year 2000 if the efficiency of control on all these sources in the year 2000 is equivalent to performance of the best device currently available (i.e., baghouse). The projections also show that, even if stringent control is achieved in the year 2000, coal-fired power plants, basic oxygen furnaces, and kraft pulp mill recovery furnaces will each emit over 50,000 tons/year of $< 2\ \mu$ particulate.

The calculation methods described above involve many assumptions and the two projection methods represent two extremes; that is, no improvement in control versus increasingly stringent controls. However, even with the assumptions involved, the calculation methods must be based on knowledge of the particle-size distribution for the specific uncontrolled source and on information regarding the percent application of each type of control device on the specific source. Without this information, it is very difficult to estimate, with any reliability, the present level of fine-particle emissions, and any attempt to make projections of these emissions would be of little value. For this reason, projections of fine-particle emissions were made only for those sources for which adequate particle size distribution data and percent of application of each major type of control device were available.

8.2 Number Basis

The number of fine particles emitted to the year 2000 by stationary sources was projected by two methods that are extensions of the techniques used to project mass emissions. The first method assumes no change in the net control from 1968 to 2000 which means that the number emissions, as were the mass emissions, are directly proportional to the projected production capacities. Method 2 utilizes the mass emissions projected by the second technique discussed in Section 8.1 and an assumption regarding the average diameter of fine particles emitted from sources in future years. The two methods are discussed in more detail in the following paragraphs.

Method 1 - This method is the same as Method 1 for the projection of mass emissions. Therefore, the number of particles emitted increases in direct proportion to increases in production capacity. Projected production figures, reported in Ref. 1, were used to proportionally increase the current number of fine particle emissions (Table 2). An example of the calculation method is given in Table 23.

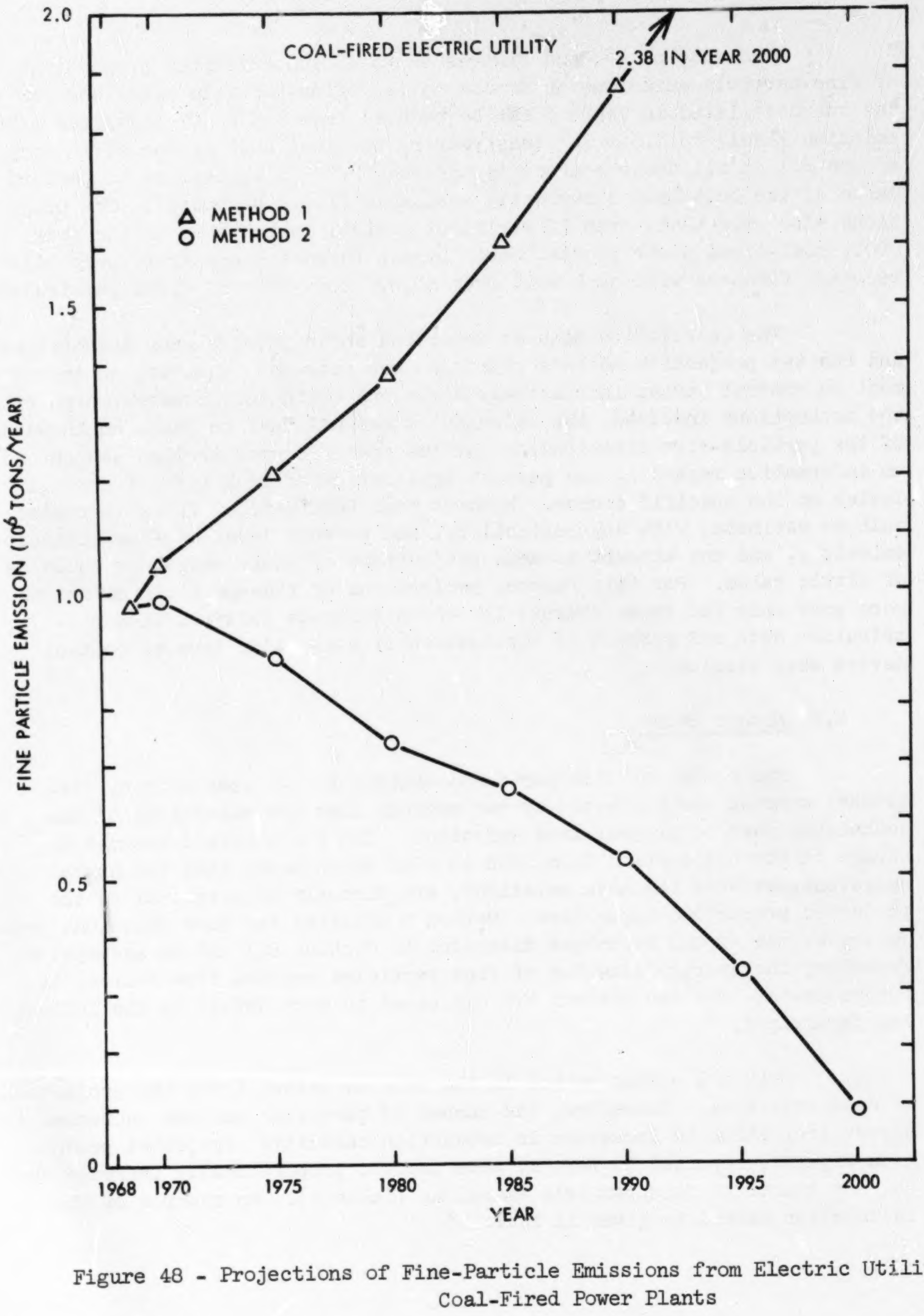

Figure 48 - Projections of Fine-Particle Emissions from Electric Utility Coal-Fired Power Plants

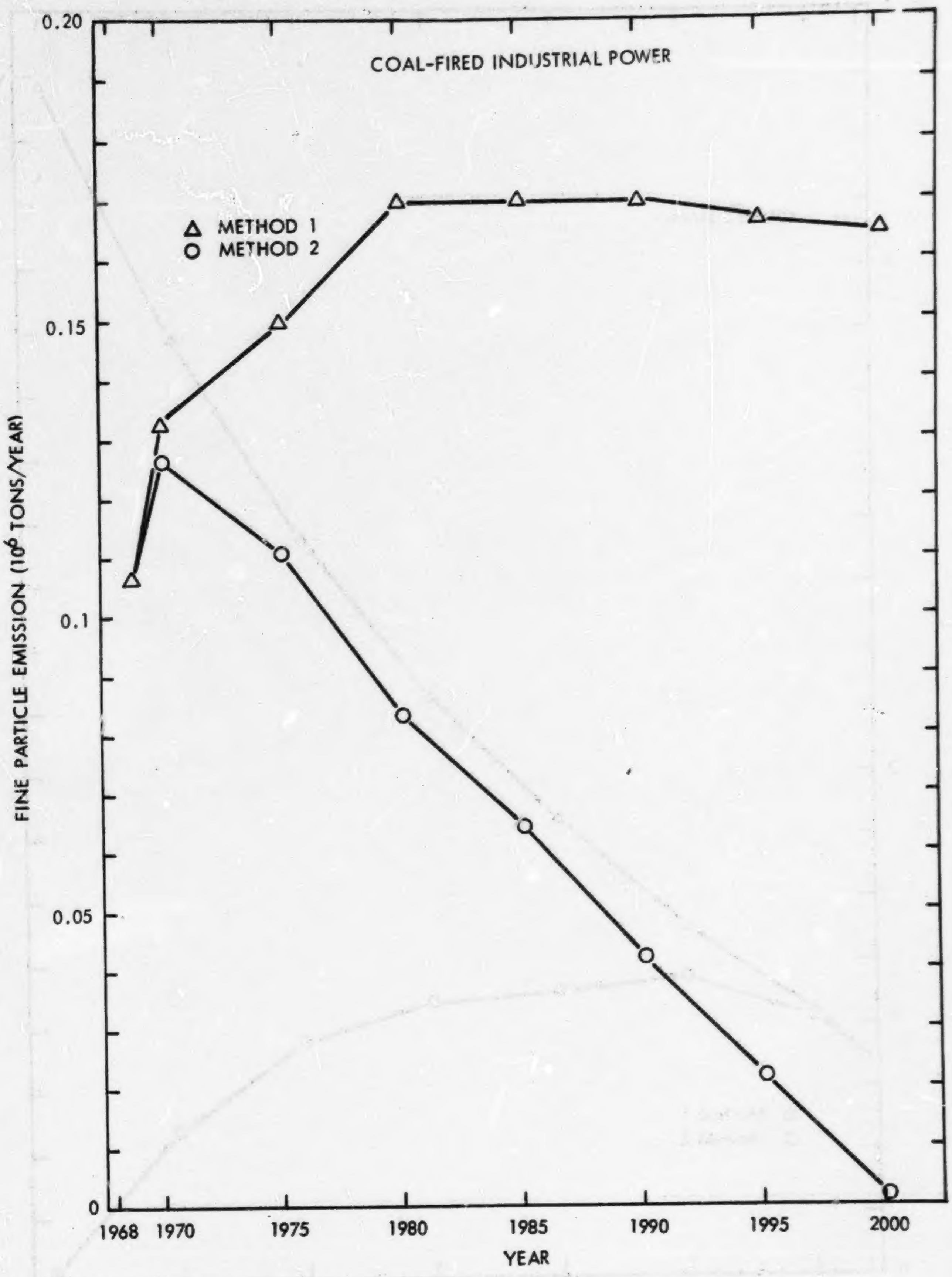

Figure 49 - Projections of Fine-Particle Emissions from Industrial Coal-Fired Power Plants

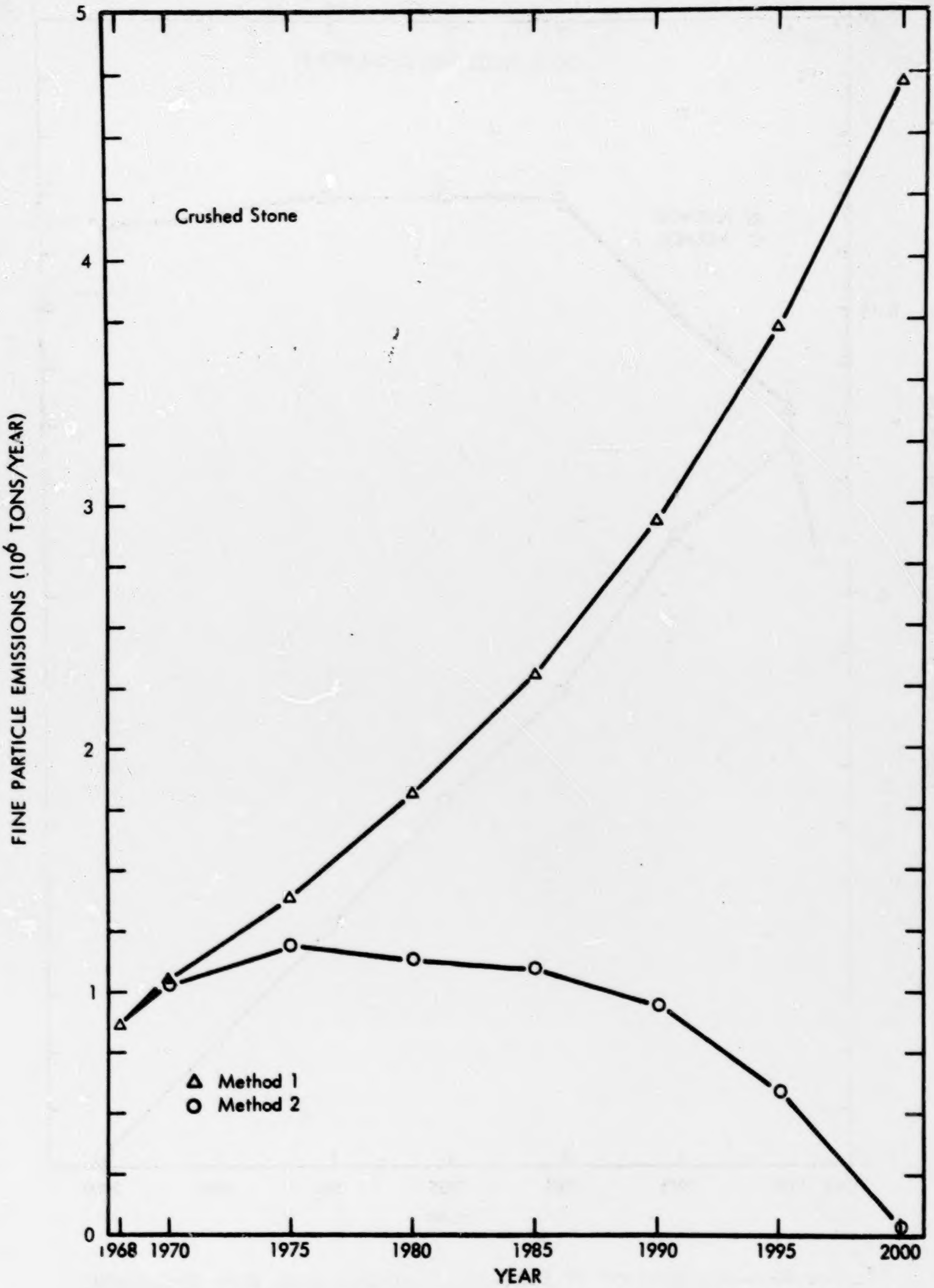

Figure 50 - Projections of Fine-Particle Emission from Crushed Stone Operations

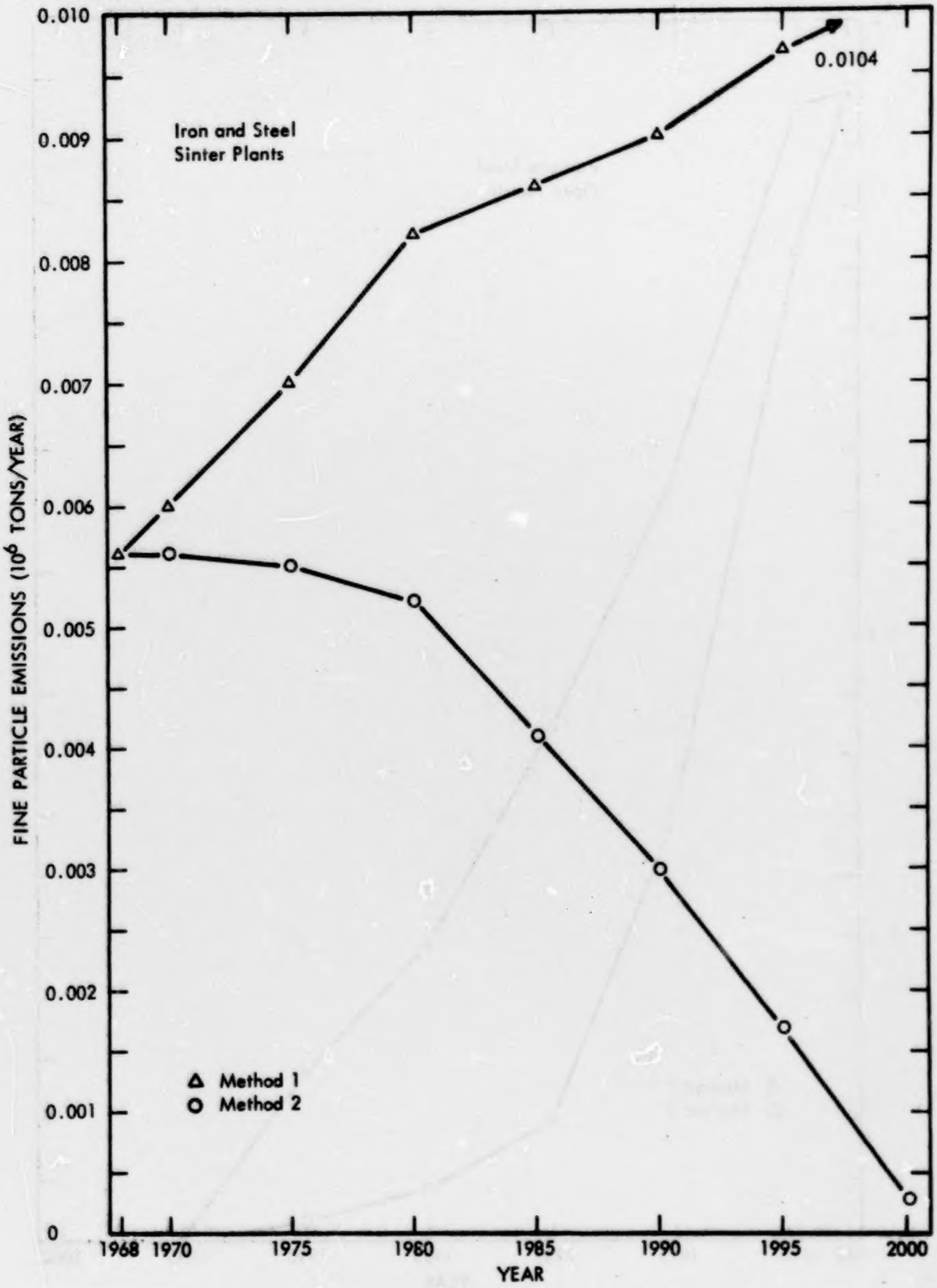

Figure 51 - Projections of Fine-Particle Emissions from Sinter Machines (iron and steel plants)

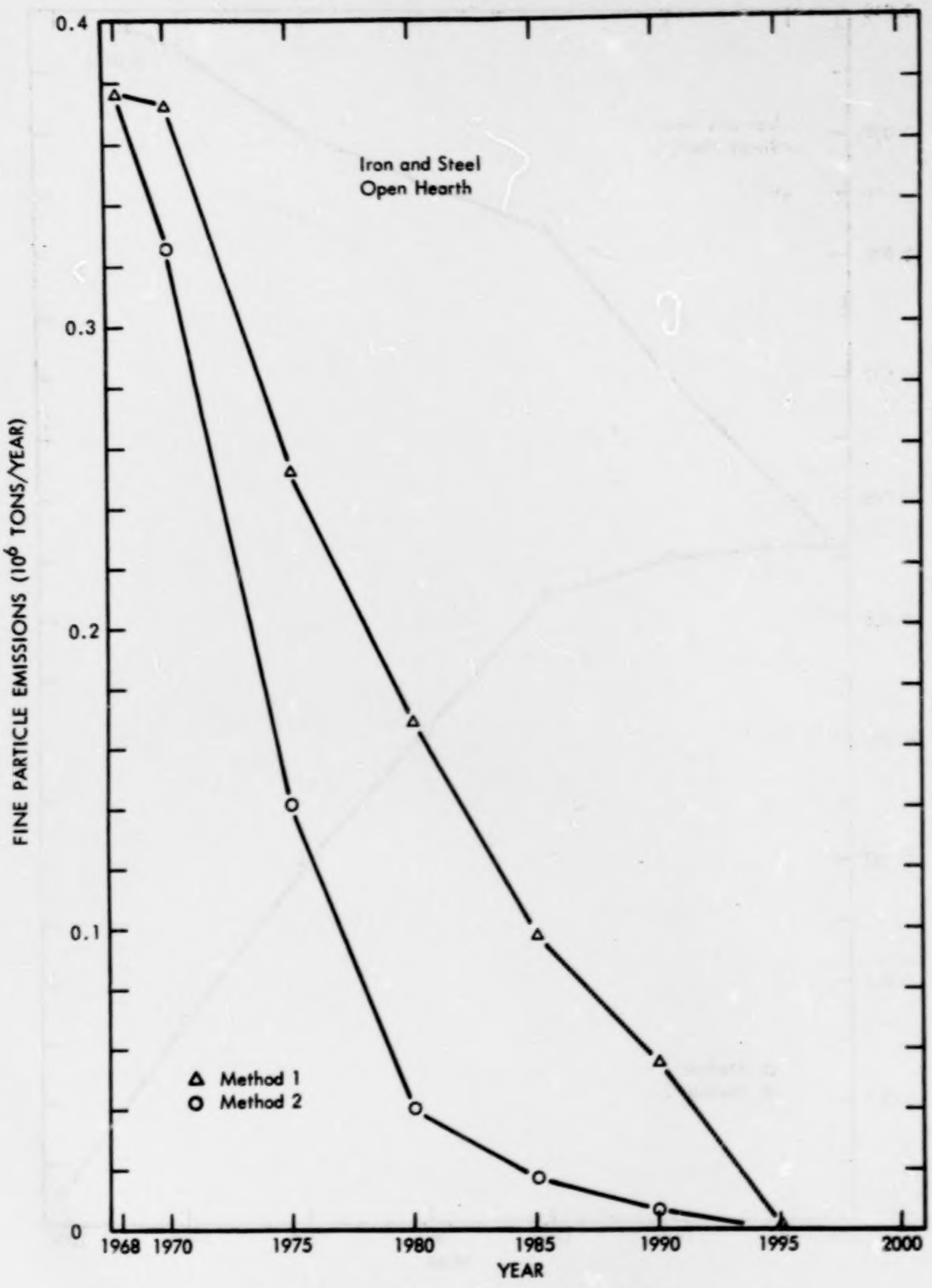

Figure 52 - Projections of Fine-Particle Emissions from Open Hearth Furnaces (iron and steel plants)

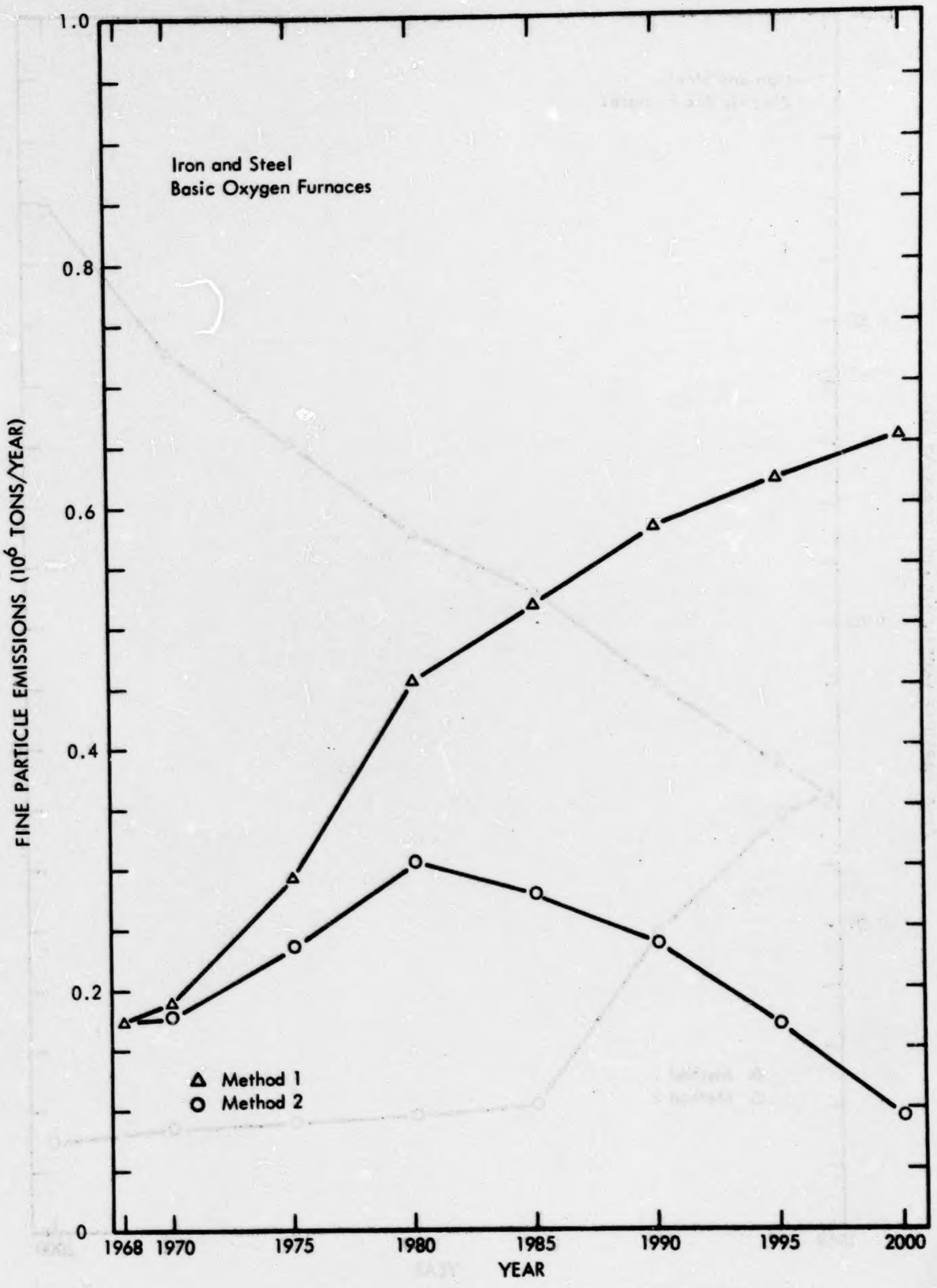

Figure 53 - Projections of Fine-Particle Emissions from Basic Oxygen Furnaces (iron and steel plants)

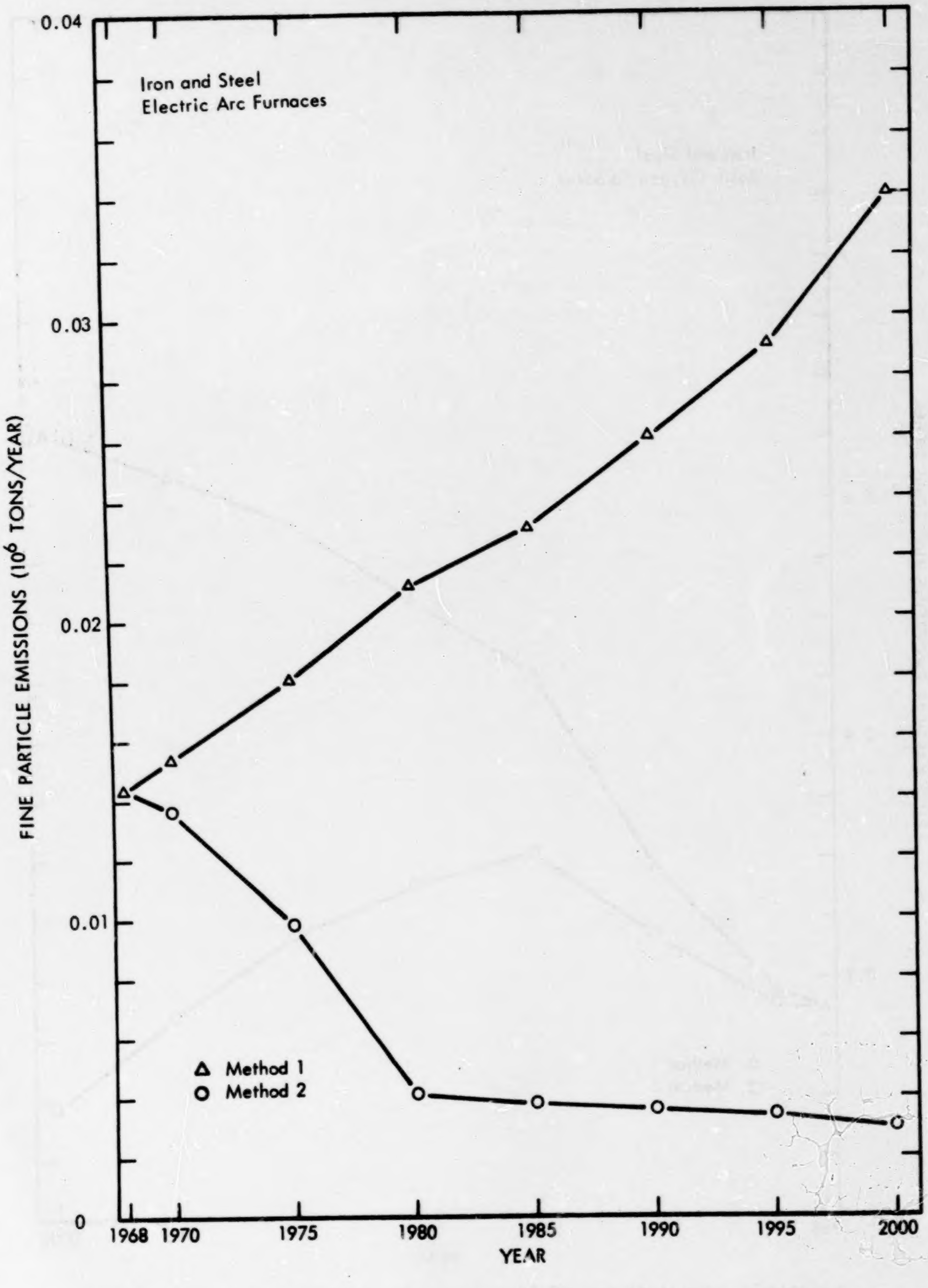

Figure 54 - Projections of Fine-Particle Emissions from Electric Arc Furnaces (iron and steel plants)

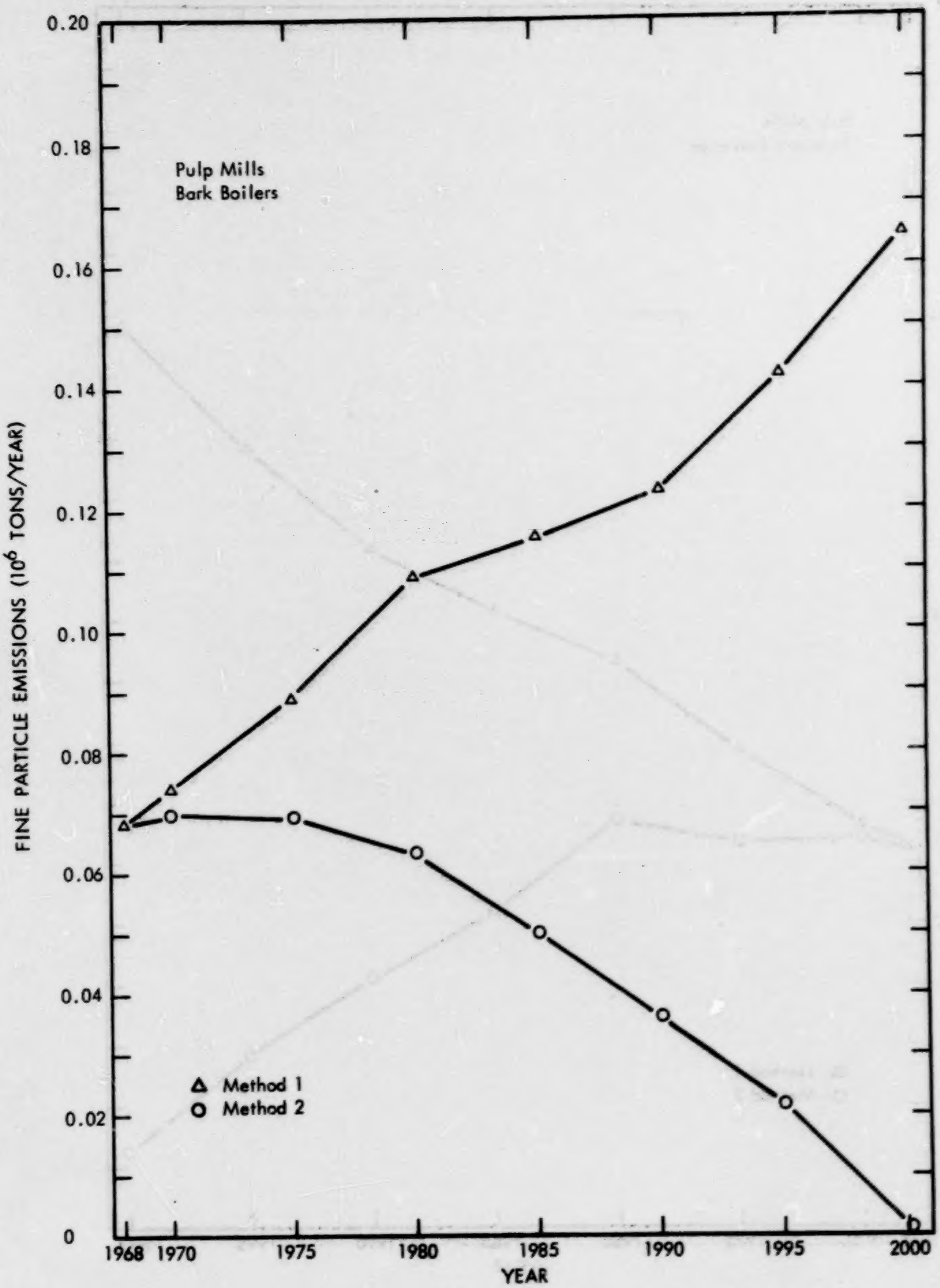

Figure 55 - Projections of Fine-Particle Emissions from Kraft Pulp Mill Bark Boilers

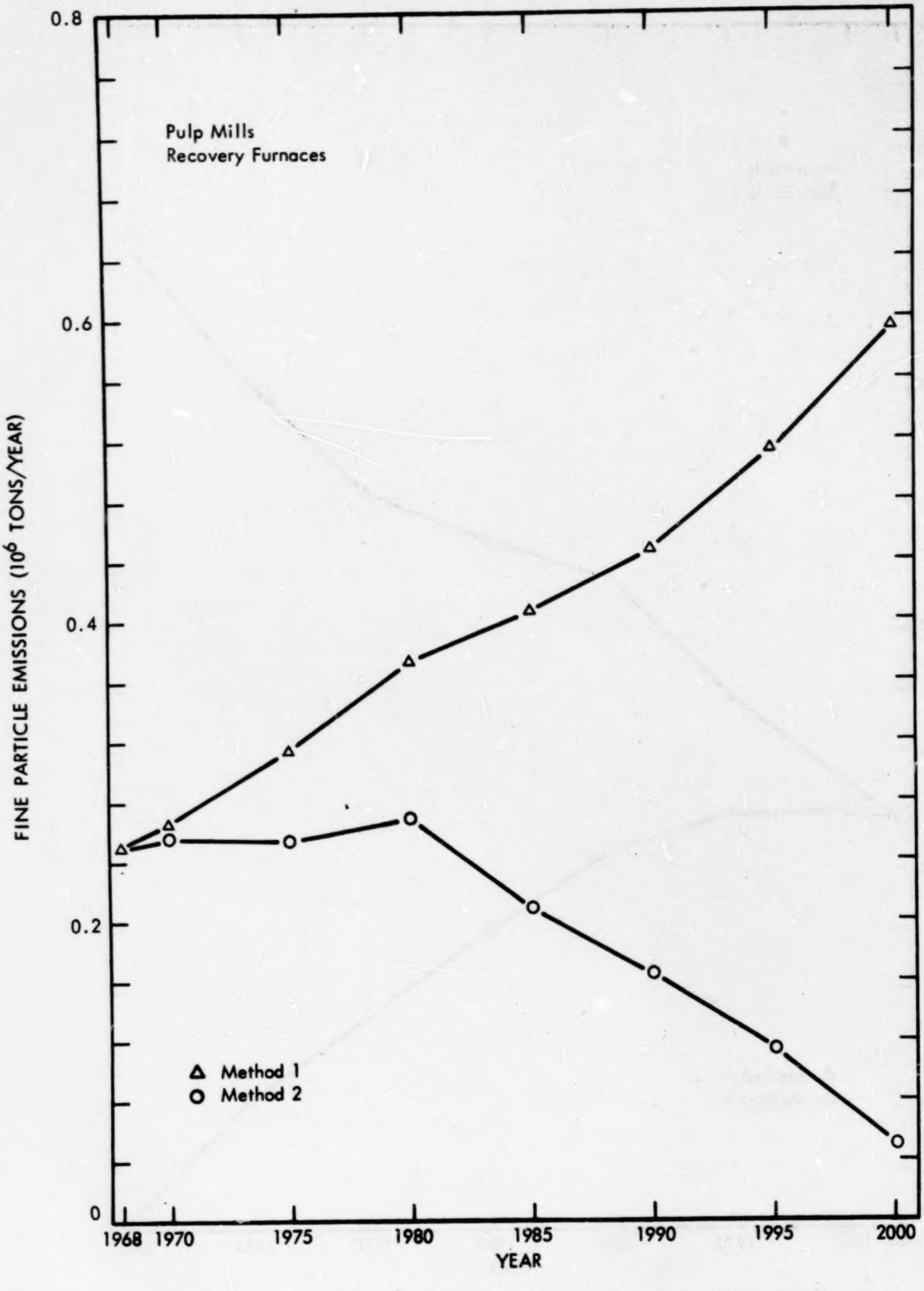

Figure 56 - Projections of Fine-Particle Emissions from Kraft Pulp Mill Recovery Furnaces

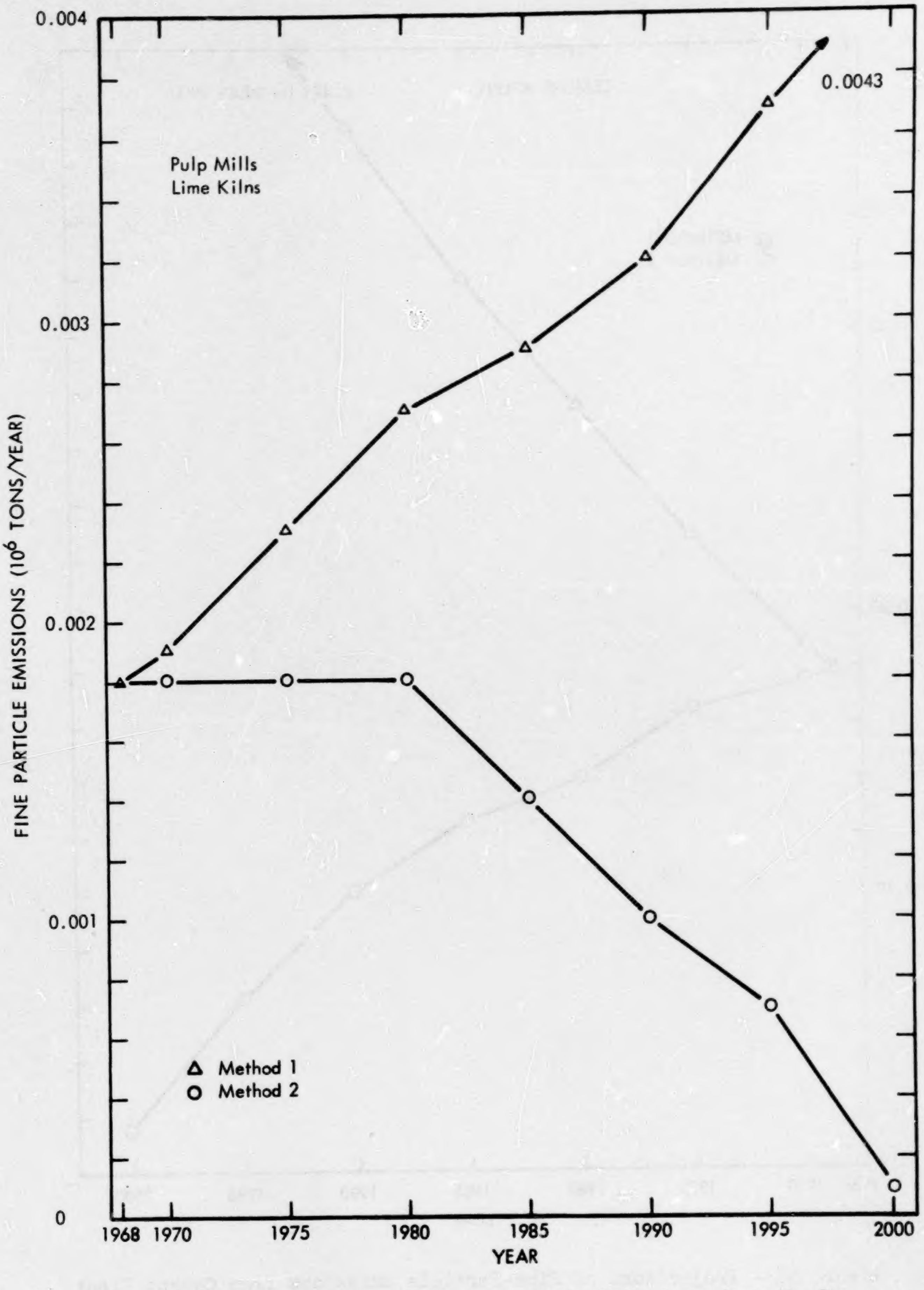

Figure 57 - Projections of Fine-Particle Emissions from Kraft Pulp Mill Lime Kilns

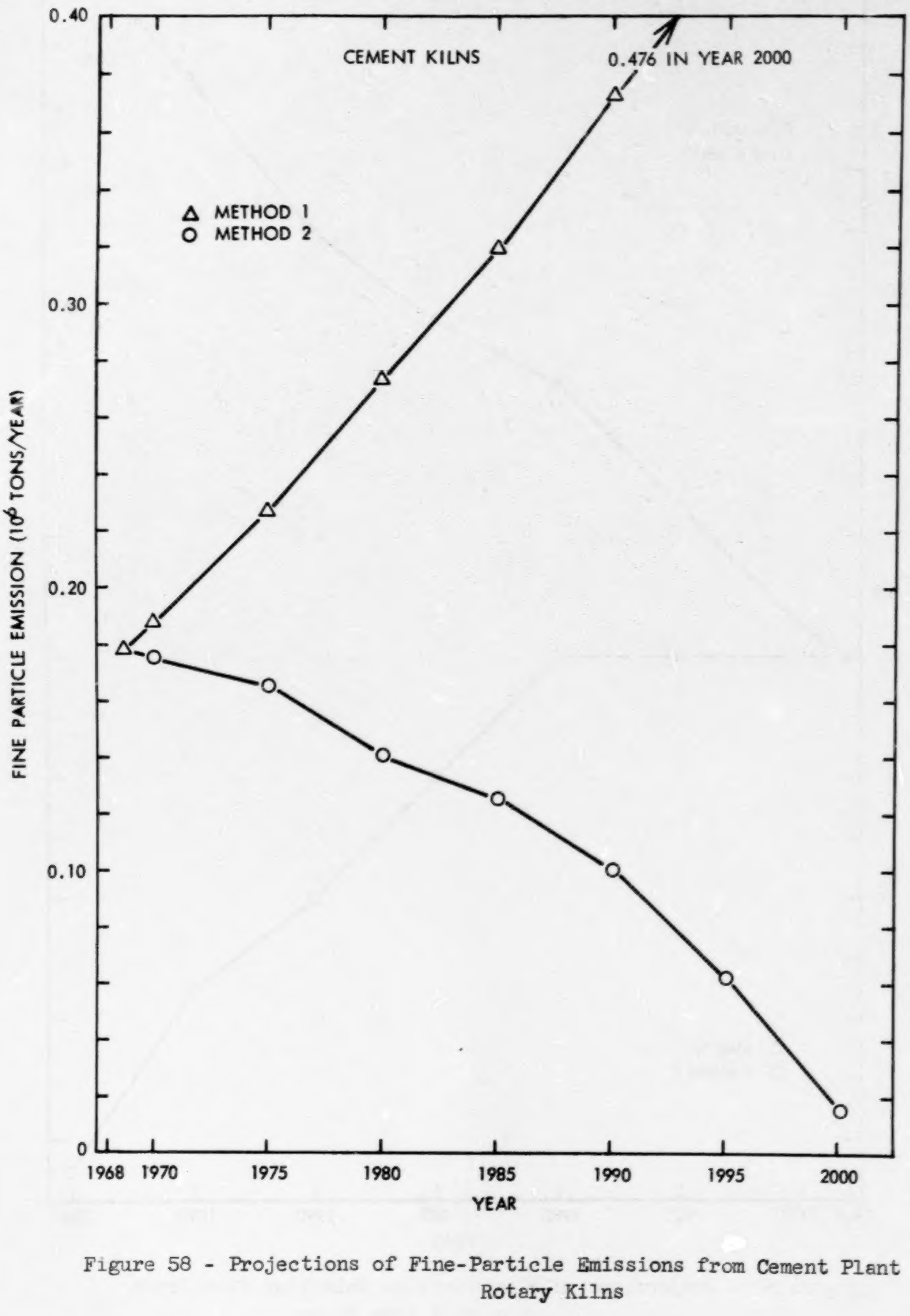

Figure 58 - Projections of Fine-Particle Emissions from Cement Plant Rotary Kilns

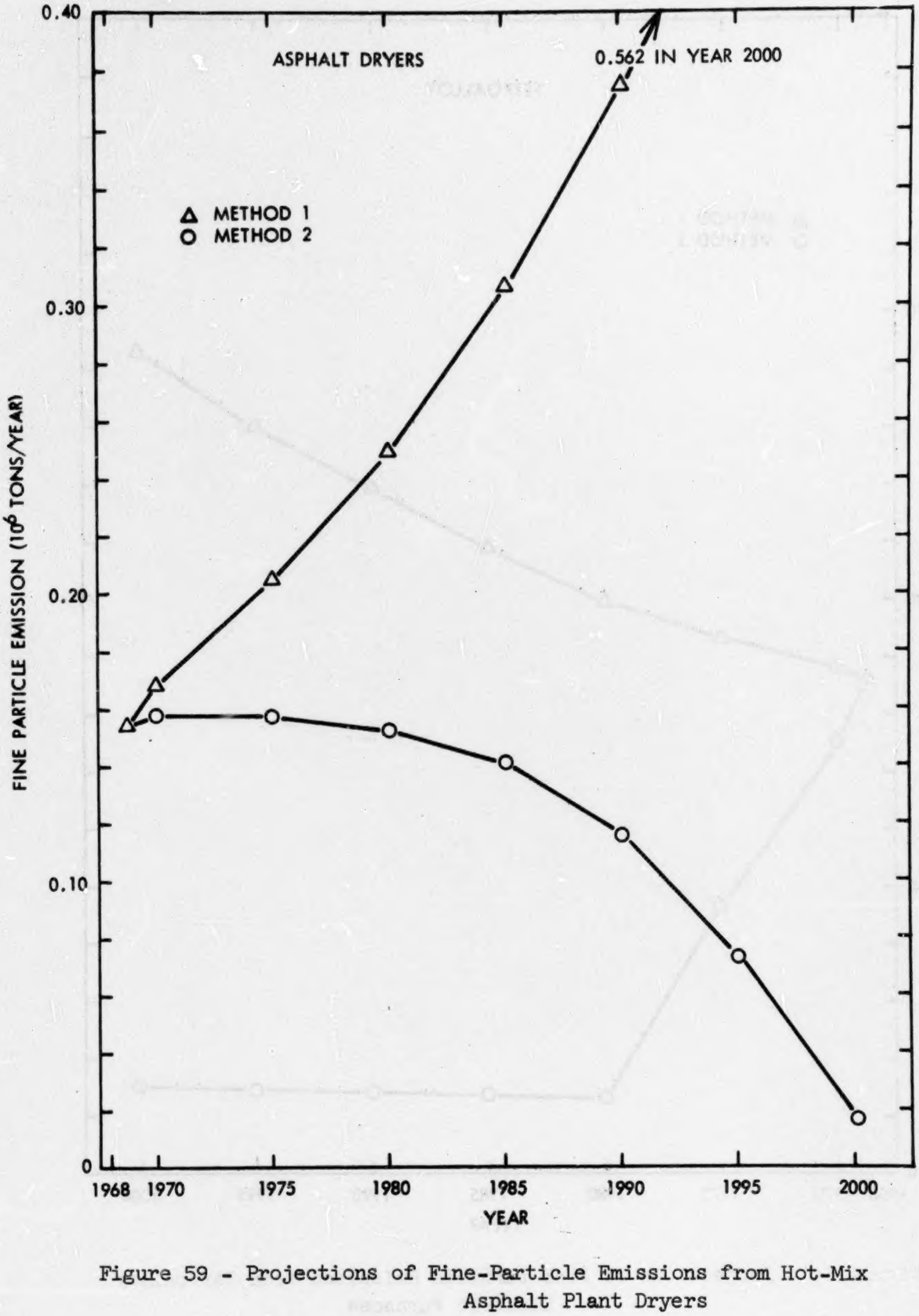

Figure 59 - Projections of Fine-Particle Emissions from Hot-Mix Asphalt Plant Dryers

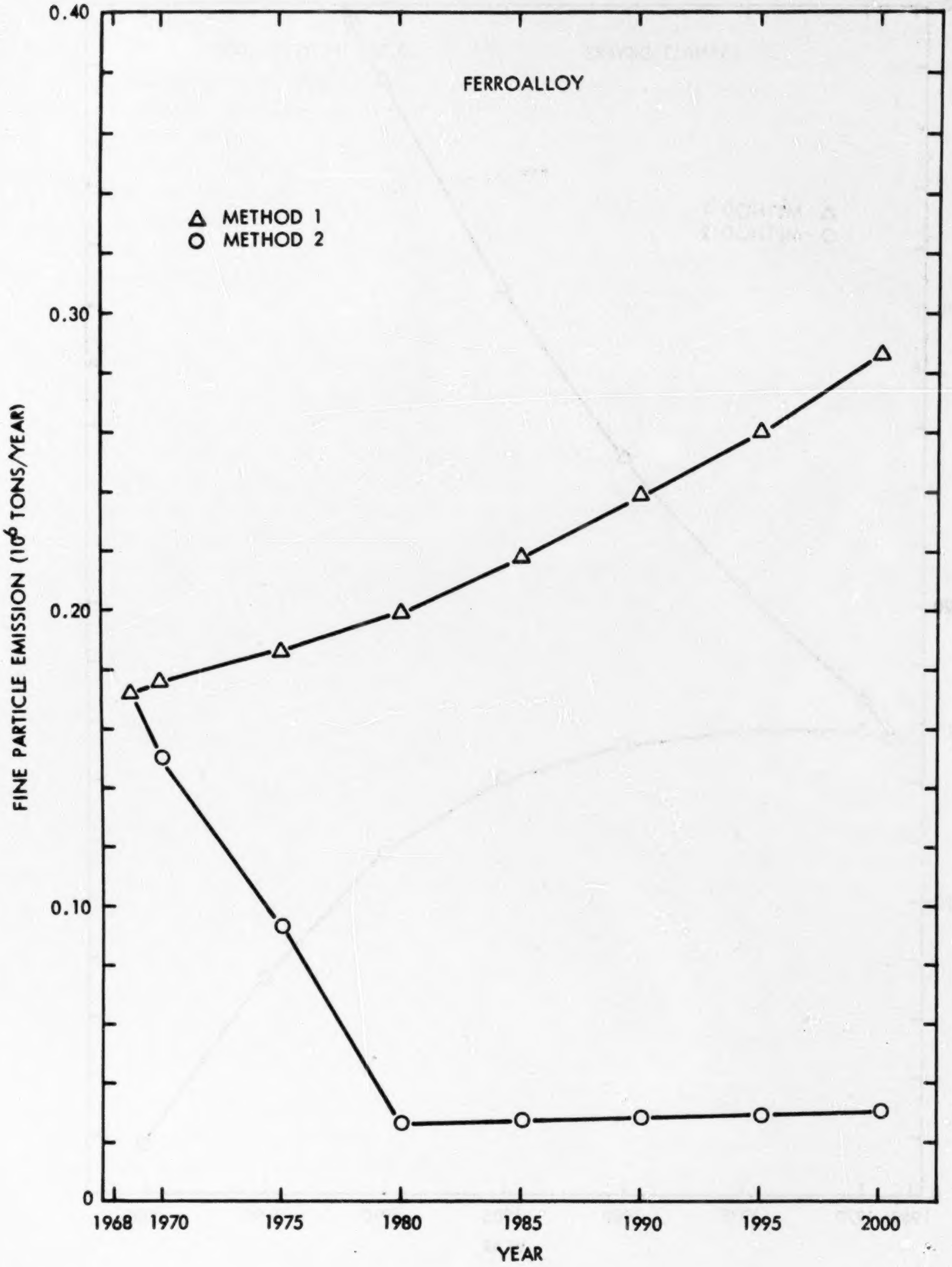

Figure 60 - Projections of Fine-Particle Emissions from Ferroalloy Electric Furnaces

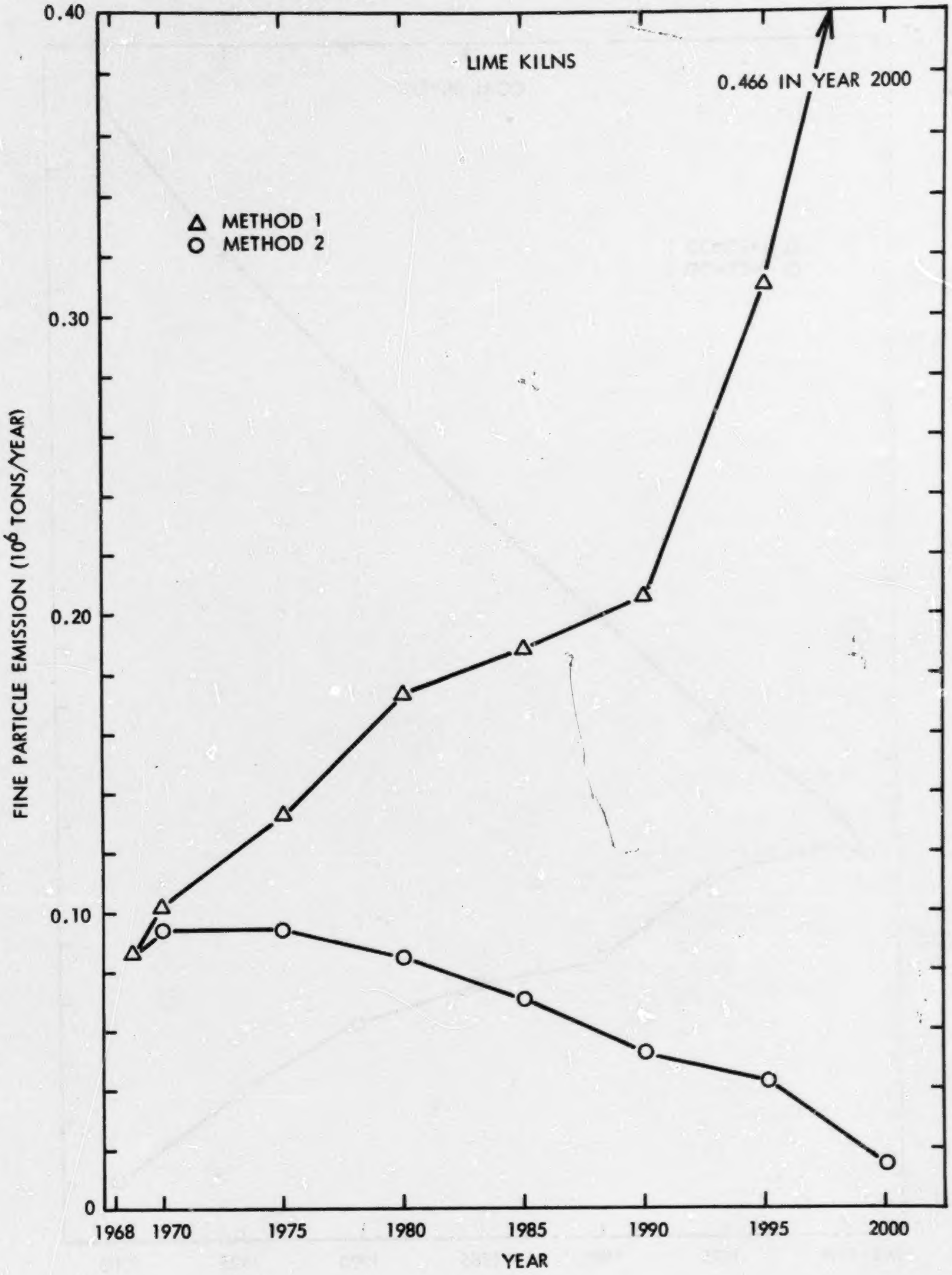

Figure 61 - Projections of Fine-Particle Emissions from Lime Plant Rotary Kilns

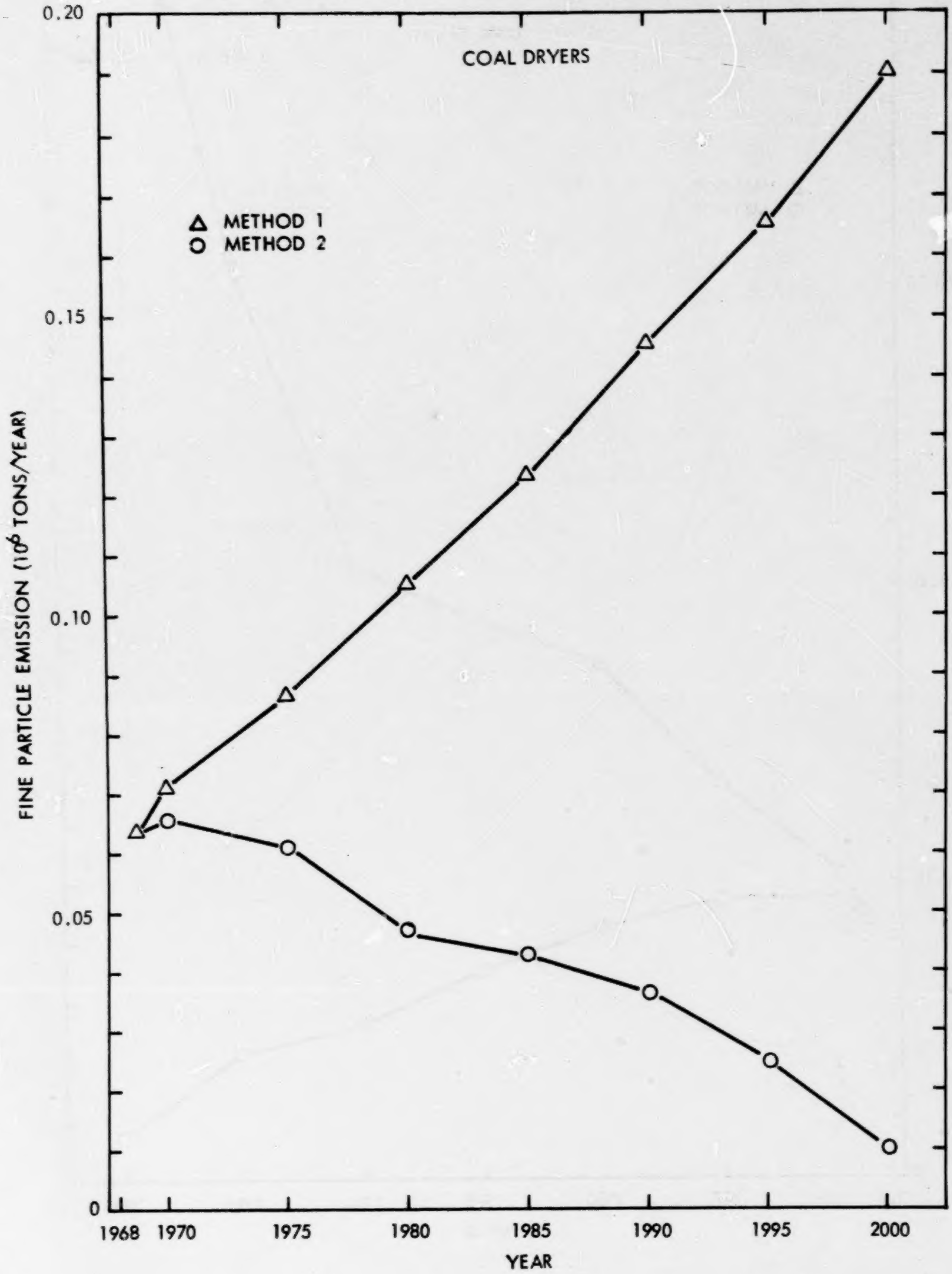

Figure 62 - Projections of Fine-Particle Emissions from Coal Preparation Plant Thermal Dryers

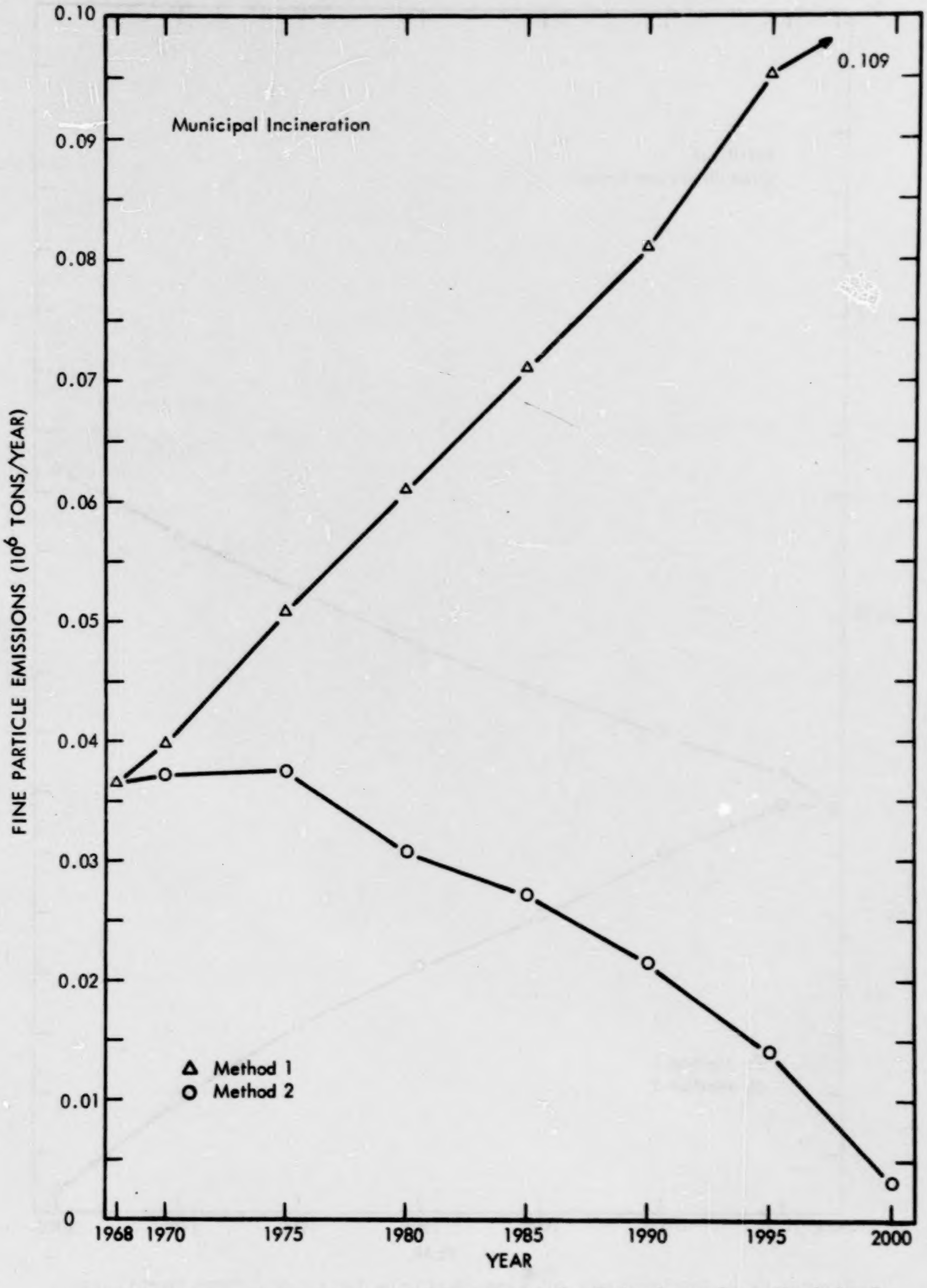

Figure 63 - Projections of Fine-Particle Emissions from Municipal Incineration

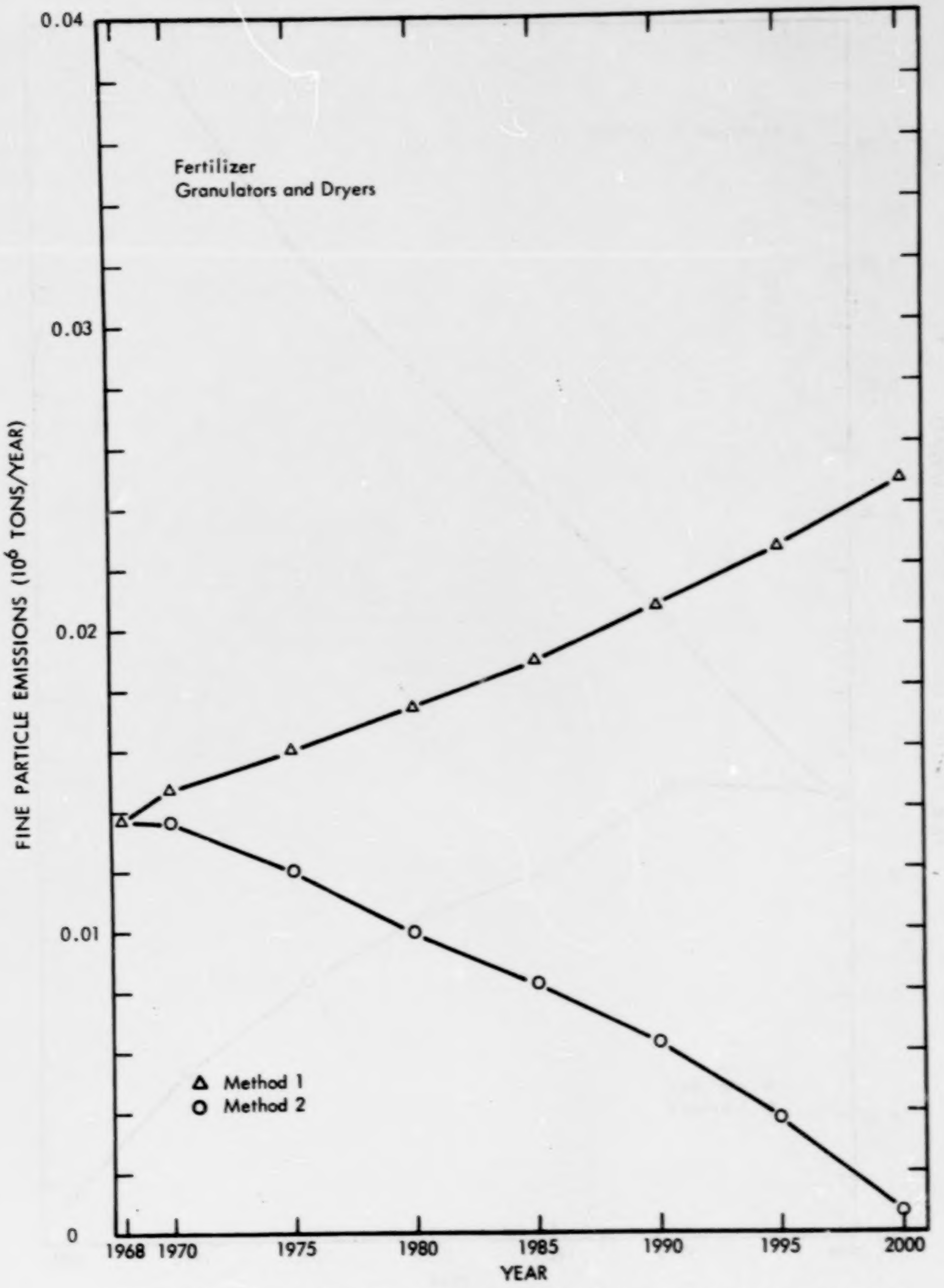

Figure 64 - Projections of Fine-Particle Emissions from Fertilizer Granulators and Dryers

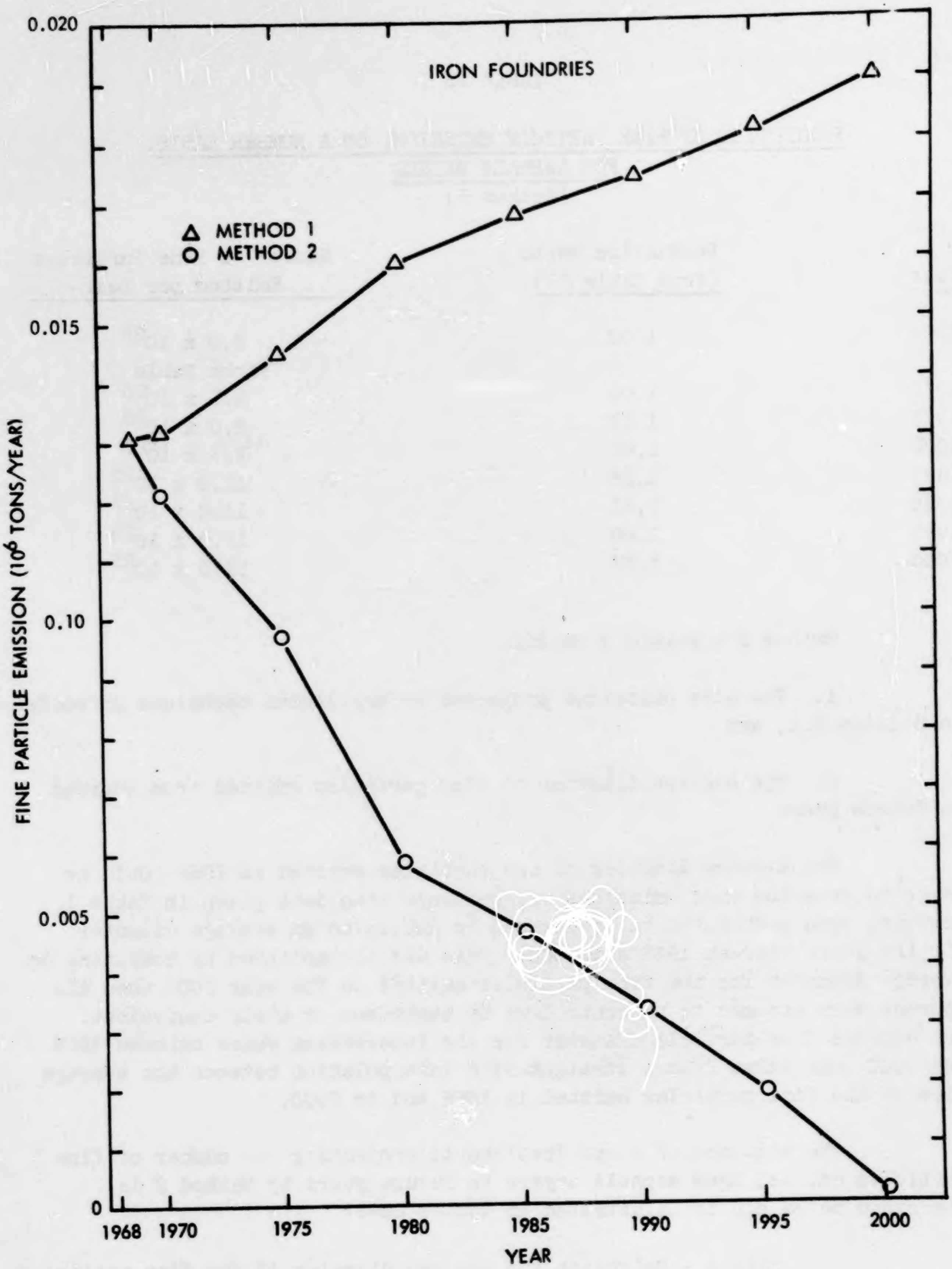

Figure 65 - Projections of Fine-Particle Emissions from Iron Foundry Cupolas

TABLE 23

PROJECTION OF FINE PARTICLE EMISSION, ON A NUMBER BASIS, FOR ASPHALT DRYERS

(Method 1)

Year	Production Ratio (from Table 20)	Number of Fine Particles Emitted per Year
1968	1.00	6.0×10^{23} (from Table 2)
1970	1.09	6.5×10^{23}
1975	1.33	8.0×10^{23}
1980	1.62	9.7×10^{23}
1985	1.98	11.9×10^{23}
1990	2.43	14.6×10^{23}
1995	2.98	17.9×10^{23}
2000	3.65	21.9×10^{23}

Method 2 - Method 2 employs:

1. The mass emissions projected by the second technique presented in Section 8.1, and

2. The average diameter of fine particles emitted from sources in future years.

The average diameter of the particles emitted in 1968 could be computed from the mass emissions vs. particle size data given in Table 1. However, some method had to be devised to determine an average diameter for the years between 1968 and 2000. This was accomplished by computing an average diameter for the fine particles emitted in the year 2000 when all sources were assumed to be controlled by baghouses or their equivalent. The average fine-particle diameter for the intervening years between 1968 and 2000 was taken from a straight-line interpolation between the average size of the fine particles emitted in 1968 and in 2000.

The sequence of steps involved in projecting the number of fine particles emitted from asphalt dryers in future years by Method 2 is described below and is illustrated in Tables 24-27.

Step 1 - Calculate the average diameter of the fine particles emitted in 1968 (see Table 24).

TABLE 24

CALCULATION OF THE AVERAGE DIAMETER OF FINE PARTICLES FROM ASPHALT DRYERS IN 1968

(Method 2)

Fine Particle Emissions = 154,200 tons/year (from Table 1)

Number of Fine Particles Emitted = 6.0×10^{23} particles/year (from Table 2)

$$\text{dmp} = \sqrt[3]{\frac{(17.3 \times 10^5)(\text{mass emission tons/year})}{(\text{density g/cm}^3)(\text{number emissions})}}$$

$$\text{dmp} = \sqrt[3]{\frac{(17.3 \times 10^5)(154.2 \times 10^3)}{(2.6^*)(6.0 \times 10^{23})}}$$

$$\text{dmp} = \sqrt[3]{171 \times 10^{-15}}$$

$$\boxed{\text{dmp} = 5.55 \times 10^{-5} \text{ cm.}}$$

---

* Density values were taken from Ref. 18.

Step 2 - Calculate the average diameter of the fine particles emitted in the year 2000. Calculation is based on the projected mass emission for the year 2000 (Method 2, Section 8.1) and on the assumption that all sources will be controlled with baghouses or the equivalent in the year 2000.

The size distribution of the particulates escaping the baghouse was computed using the size distribution of the particles emitted from the uncontrolled source and the fractional efficiency curve for a fabric filter (Figure 17). For most sources, this had already been done in conjunction with computing the mass emissions of fine particles. The size distribution of the particles emitted from the baghouse and the projected total mass emissions of fine particles for the year 2000 are then used to calculate the mass emission of fine particles within each size range. The mass emission within each size range is in turn used to calculate the number of particles emitted within each size range. Knowing the total mass and total number of fine particles emitted, the average diameter can be calculated. Table 25 presents an example calculation.

TABLE 25

CALCULATION OF THE AVERAGE DIAMETER OF FINE PARTICLES FROM ASPHALT DRYERS IN THE YEAR 2000

(Method 2)

A. Calculate Mass Emissions Within Each Size Range

1-3 µ $\quad \frac{0.06}{0.12} = 50\% \times 18{,}200$ tons/year = 9,100 tons/year

(from Table 20) (from Table 22)

0.5-1 µ $\quad \frac{0.04}{0.12} = 33\% \times 18{,}200$ tons/year = 6,000 tons/year

0.1-0.5 µ $\quad \frac{0.02}{0.12} = 17\% \times 18{,}200 \text{ tons/year} = \frac{3{,}100}{18{,}200 \text{ tons/year}}$

B. Calculate Number of Particles Emitted Within Each Size Range

1-3 µ $$N = \frac{(17.3 \times 10^5 \text{ g/ton})(9.1 \times 10^3 \text{ tons/year})}{(2.6 \text{ g/cm}^3)(2 \times 10^{-4} \text{ cm.})^3} = 7.6 \times 10^{20} \text{ particles/year}$$

0.5-1 µ $$N = \frac{(17.3 \times 10^5)(6.0 \times 10^3)}{(2.6)(0.75 \times 10^{-4})^3} = 94.6 \times 10^{20}$$

0.1-0.5 µ $$N = \frac{(17.3 \times 10^5)(3.1 \times 10^3)}{(2.6)(0.30 \times 10^{-4})^3} = 764.0 \times 10^{20}$$

$$\Sigma N = 866 \times 10^{20} \text{ particles/year}$$

C. Calculate Average Diameter of Fine Particles

$$dmp = \sqrt[3]{\frac{(17.3 \times 10^5 \text{ g/ton})(18.2 \times 10^3 \text{ tons/year})}{(2.6 \text{ g/cm}^3)(0.866 \times 10^{23} \text{ particles/year})}}$$

$$\boxed{dmp = 5.19 \times 10^{-5} \text{ cm.}}$$

Step 3 - The data to be used in projecting the number of fine particles emitted by asphalt dryers are compiled as shown in Table 26. The average particle diameters for the years between 1968 and 2000 were obtained by straight-line interpolation between the average diameter for the year 1968 and the year 2000 as discussed in Steps 1 and 2. The mass emission of fine particles was taken from previous projection of these emissions (Method 2, Section 8.1).

Step 4 - The data compiled in Step 3 are used to calculate the number of fine particles emitted, up to year 2000, as shown in Table 27.

Table 7, page 14, summarizes the results of the projections of fine-particle emissions on a number basis. The projections show that ferroalloy electric furnaces, rotary lime kilns in lime plants, municipal incinerators, coal-fired power plants, and steel making furnaces (BOF and electric arc) will be significant sources of fine-particle pollutants, on a number basis, even with stringent control in the year 2000.

TABLE 26

COMPILATION OF DATA TO BE USED IN PROJECTION OF NUMBER OF FINE PARTICLES EMITTED FROM ASPHALT DRYERS

(Method 2)

Year	Average Diameter of Fine-Particle Emissions (dmp)	Fine-Particle Mass Emissions (tons/year)(from Table 23)
1968	5.55×10^{-5} cm. (from Table 24)	154,200
1970	5.53×10^{-5}	157,600
1975	5.47×10^{-5}	157,700
1980	5.42×10^{-5}	152,000
1985	5.36×10^{-5}	140,800
1990	5.30×10^{-5}	116,500
1995	5.25×10^{-5}	74,100
2000	5.19×10^{-5} cm. (from Table 25)	18,200

TABLE 27

PROJECTION OF FINE-PARTICLE EMISSIONS ON A NUMBER BASIS FOR ASPHALT DRYERS

(Method 2)

Year	(Refer to Table 26)	No. of Fine Particles Emitted Per Year
1968		$= 6.0 \times 10^{23}$ (from Table 2)
1970	$N = \dfrac{(17.3 \times 10^5 \text{ g/ton})(157.6 \times 10^3 \text{ tons/year})}{(2.6 \text{ g/cm}^3)(5.53 \times 10^{-5} \text{ cm.})^3}$	$= 6.2 \times 10^{23}$
1975	$N = \dfrac{(17.3 \times 10^5)(157.7 \times 10^3)}{(2.6)(5.47 \times 10^{-5})^3}$	$= 6.4 \times 10^{23}$
1980	$N = \dfrac{(17.3 \times 10^5)(152.0 \times 10^3)}{(2.6)(5.42 \times 10^{-5})^3}$	$= 6.3 \times 10^{23}$
1985	$N = \dfrac{(17.3 \times 10^5)(140.8 \times 10^3)}{(2.6)(5.36 \times 10^{-5})^3}$	$= 6.1 \times 10^{23}$
1990	$N = \dfrac{(17.3 \times 10^5)(116.5 \times 10^3)}{(2.6)(5.30 \times 10^{-5})^3}$	$= 5.2 \times 10^{23}$
1995	$N = \dfrac{(17.3 \times 10^5)(74.1 \times 10^3)}{(2.6)(5.25 \times 10^{-5})^3}$	$= 3.4 \times 10^{23}$
2000	$N = \dfrac{(17.3 \times 10^5)(18.2 \times 10^3)}{(2.6)(5.19 \times 10^{-5})^3}$	$= 0.87 \times 10^{23}$

9. Conclusions and Recommendations

9.1 Conclusions

1. An accurate assessment of the mass of fine particles emitted from specific sources was precluded because neither particle size distribution data nor fractional efficiency curves for control devices were available in the 0.01-2 μ size range. The lack of particle size data for effluents from controlled sources indicates that neither control equipment manufacturers nor air pollution control agencies have placed any emphasis on the particle size of material emitted from control equipment.

2. Fine-particle emissions from industrial sources of particulate pollution are estimated to be at least 4 x 10^6 tons/year. This represents approximately 20-25% of the total mass emissions for these sources.

3. Major industrial sources of fine particles, based on mass and number emitted, include: (a) ferroalloy furnaces, (b) steelmaking furnaces, (c) electric utility power plants, (d) lime kilns, (e) kraft pulp mill recovery furnaces, (f) municipal incinerators, and (g) iron foundries.

4. Discrepancies exist in the fine-particle and total mass emissions from some sources that emit mainly micron or submicron particulates (e.g., basic oxygen furnaces and kraft pulp mill recovery furnaces). Analysis of the possible causes of these discrepancies led to observation that erroneous conclusions may have been reached regarding the high overall mass efficiency of control equipment on these sources.

5. Currently, control equipment is rated by one parameter, namely, overall mass efficiency. Specification of control equipment efficiency by overall performance is inadequate with respect to small particles. Penetration (i.e., 1-mass efficiency) in specific size ranges is a more revealing term for rating control equipment performance.

6. There is considerable doubt that present air pollution control procedures, which are based on overall percentage reduction in emissions (tons/year), actually achieve the desired reduction in suspended particulate matter in the community air.

7. Fractional efficiency characteristics of control devices have not been accurately determined, and, as a result, the ability of control devices to collect < 2 μ particles is ill-defined.

8. A major portion (over 95%) of the data currently available on the particle size of particulates emitted from industrial sources has been obtained by sampling and particle sizing techniques that are not suitable

for the particle size range $< 2\ \mu$. As a result, only a meager quantity of accurate data is available on particle size in the $< 2\ \mu$ size range for effluents from uncontrolled or controlled sources.

9. Fine particulates emitted from man's activity contribute significantly to all the major adverse aspects of air pollution. Fine particles can initiate or contribute to problems related to human health, atmospheric physical properties, and/or material degradation. The chemical and physical properties of the atmosphere affected include: its electrical properties; its ability to transmit radiant energy; its ability to convert water vapor to fog, cloud, rain, and snow; its ability to damage and to soil surfaces.

10. The effects of particulate matter on human health are, for the most part, related to injury to the surfaces of the respiratory system.

11. A combination of particulates and gases may produce an effect on human health that is greater than the sum of the effects caused by either individually (i.e., synergistic effects).

9.2 Research Recommendations

1. Source sampling with more advanced instrumentation (e.g., cascade impactors, thermal precipitators, and electrostatic precipitators) must be done to define the effectiveness of control equipment for the collection of particulate pollutants. Standard sampling techniques are inadequate for collecting and sizing particles, particularly for particles $1\ \mu$ or smaller. The program should involve actual field testing, and attention should be directed to the determination of the particle-size distribution before and after control equipment and the fractional efficiency of specific control devices on specific sources.

2. Current control devices do not adequately collect fine particles. Therefore, research programs should be initiated to study methods for the collection of fine particulates. Research should be directed to these main areas: (a) improvement of existing control equipment via better design, (b) development of new and/or novel devices for controlling fine particles, and (c) agglomeration mechanisms of fine particles. Research on the agglomeration mechanisms should improve existing collector performance and may lead to new collector devices.

3. Current capability to monitor, sample, and size effluents from particulate pollution sources is inadequate. Research should be initiated to improve this capability. Optical techniques for monitoring fine particle emissions should be pursued. Simple, yet reliable stack sampling methods need to be developed. A collection mechanism which collects

submicron particles and causes neither a formation nor a break-up of aggregates is necessary if accurate particle size information is to be obtained.

4. Research should be directed to defining the relationships between total suspended particulate in the air and specific sources of particulate pollution. Information is needed to help identify the origins of suspended particles in the air and to assess the contribution of various sources to the total particulate burden in the atmosphere. Investigations should focus on material that leaves the source as a particulate (i.e., primary particulate), and source effluents that form particulates after leaving the source (i.e., secondary particulates). Reduction of total suspended particulate matter may require control at the source of effluents that form secondary particulates.

5. Epidemiological and laboratory studies of the effects of particulate pollutants on humans, including experiments on animals, should be carefully coordinated and selectively accelerated. Attention should be focused on synergistic effects produced by gases in combination with particulates.

6. Information on chemical composition of particulate pollutants as a function of particle size should be obtained to assist in defining potential health hazards of particulate pollutants. Attention should be focused on potentially harmful metals.

7. Material damage caused by fine particulate pollutants should be assessed more closely.

8. The influence of suspended-particulate matter on the behavior of the atmosphere should be defined in more detail. Attention should be focused on their effect on solar radiation and weather modification.

9. Since the major adverse effects of particulate pollutants on human health and welfare are associated with micron and submicron particles, the technical and economic feasibility of establishing national emission standards based on particle size should be investigated. Performance or emission standards based on particle size should be studied because there is great doubt that present procedures which are based on overall percentage reduction in emissions (tons/year) actually achieve the desired reduction in suspended particulate matter in the community air. If a performance standard based on particle size were adopted, accurate data expressing control equipment efficiency over the various particle size ranges will be necessary. Simple, accurate, and reliable methods for testing the performance of various control devices in the fine-particle range will also be needed. These test procedures will be needed to confirm compliance of installed equipment with regulations as well as to provide a means of

comparing performance capabilities of various devices on a single source. Research recommendations 1 and 3 would provide input to this area. More stringent regulations will produce substantial costs in design, engineering, and testing. Data on those costs will need to be accumulated. Also more analytical data on the dependence of control equipment performance on source operating variables and effluent characteristics will need to be developed, industry by industry.

REFERENCES

1. Particulate Pollutant System Study, Volume I, NAPCA Contract CPA 22-69-104, Midwest Research Institute, 1 May 1971.

2. Bosch, J. C., "Size Distributions of Aerosols Emitted from a Kraft Mill Recovery Furnace," M. S. Thesis, University of Washington, 1969.

3. "A Manual of Electrostatic Precipitator Technology," Southern Research Institute, pp. 418-73, August 1970.

4. Stairmand, C. J., "The Design and Performance of Modern Gas-Cleaning Equipment," Journal of the Institute of Fuel, 58-81, February 1956.

5. Sargent, G. D., "Dust Collection Equipment," Chemical Engineering, 130-50, January 27, 1969.

6. Stairmand, C. J., "The Design and Performance of Cyclone Separators," Trans. Inst. Chem. Engrs., 29, 356-83 (1951).

7. Peterson, C. M., and K. T. Whitby, "Fractional Efficiency Characteristics of Unit Type Collectors," ASHRAE Journal Reprint, May 1965.

8. Caplan, K. J., "Collection Efficiency of Reverse-Jet Filters and Cloth Arrestors," Report prepared for National Center for Air Pollution Control, September 1968.

9. Venturini, J. L., "Operating Experience with a Large Baghouse in the Electric Arc Furnace Steelmaking Shop at Bethlehem Steel Corporation's Los Angeles Plant," presented at 63rd Annual Air Pollution Control Association Meeting, June 1970.

10. Colley, D. G., "Stack Sampling Yields Fractional Efficiencies for Dust Collectors," presented at Air Pollution Control Conference, Purdue University, October 1970.

11. Valentin, F. H. H., "The Design and Performance of Cyclone Separators," The South African Industrial Chemist, 27-35, February 1958.

12. Pinchak, A. C., "A Review of the State of the Art of Cyclone Type Separators," Clearinghouse, U.S. Department of Commerce, March 1967.

13. Gallaer, C. A., and J. W. Schindeler, "Mechanical Dust Collectors," Journal of the Air Pollution Control Association, 13(12), 574-79.

14. Bush, A. F., and E. S. C. Bouler, "Electron Microscopy Studies of a Coal-Fired Steam-Electric Generating Stack Discharge," University of California, December 1965.

15. "Louisville Air Pollution Study," Report for USDHEW, Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio (1961).

16. Herdan, G., *Small Particle Statistics*, London, Butterworths (1960).

17. Collins, T. T., Jr., "Pilot Plant Study of a Multiclone Unit Operating on Stack Gases from a Lime Kiln," TAPPI, March 1948.

18. *Particulate Pollutant System Study*, Volume III, NAPCA Contract CPA 22-69-104, Midwest Research Institute, 1 May 1971.

19. Stern, A. C., *Air Pollution*, Vol. 3, pp. 488-489, New York, Academic Press (1968).

20. Op cit., Ref. 3.

21. Bay Area Air Pollution Control District Library, Accession No. 8317.

22. Sommerlad, Robert S., "Fabric Filtration - State of the Art," Livingston, New Jersey, Foster Wheeler Corporation, March 6, 1967.

23. Gosselin, A. E., and L. W. Lemon, "Bag Filterhouse Pilot Installation on a Coal-Fired Boiler - Preliminary Report and Objectives," Proceedings of the American Power Conference, Vol. 28 (1966).

24. Pilpel, N., "Industrial Gas Cleaning," *Brit. Chemical Engr.*, 542-550, August 1960.

25. Watkins, E. R., and K. Darby, "The Application of Electrostatic Precipitation to the Control of Fume in the Steel Industry," *Scrap Iron and Steel Inst.*, pp. 24-37.

26. Little, A., "Practical Aspects of Electrostatic Precipitator Operation--Experiments on a Pilot Plant," *Trans. Inst. Chem. Engrs.*, **34**, 259-68 (1956).

27. Engelbrecht, Heinz L., "Electrostatic Precipitators in Thermal Power Stations Using Low Grade Coal," Proceedings of the 28th American Power Conference, April 1966.

28. Tuhs, Wolfgang, "Manufacture of Aerosols and Separation of Ultrafine Dusts in Spray Washers," *Staub*, **29**, 43-48, February 1969.

29. Sutton, P., "Air Pollution in Petroleum Refining," Chem. Proc. Engr., 96-100, February 1968.

30. "Atmospheric Emissions from Thermal-Process Phosphoric Acid Manufacture," Public Health Service Report, October 1968.

31. "Nationwide Inventory of Air Pollutant Emissions - 1968," USDHEW NAPCA Pub. No. AP-73, August 1970.

32. Niessen, Walter R., and Adel F. Sarofim, "The Emission and Control of Air Pollutants from the Incineration of Municipal Solid Waste," Proceedings of the Second International Clean Air Congress, December 1970.

33. Horauth, Helmuth, and August T. Rossano, "Technique for Measuring Dust Collector Efficiency as a Function of Particle Size," Proceedings of the 62nd Meeting of the Air Pollution Control Association, June 1969.

34. Kalika, Peter W., "How Water Recirculation and Steam Plumes Influence Scrubber Design," Chem. Engr., 133-138, July 1969.

35. Schell, T. W., "Cyclone/Scrubber System Quickly Eliminates Dust Problem," Rock Products, 66-68, July 1968.

36. Dickie, Lou, "All About Wet Collectors," Air Engineering, 24-27, February 1967.

37. Brink, J. A., and C. E. Contant, "Experiments on an Industrial Venturi Scrubber," 132nd Meeting, American Chemical Society, New York, New York, September 1957.

38. Training Program - National Center for Air Pollution Control.

39. Turner, B., "Grit Emissions," BAAPCD Library, Accession No. 9775.

40. National Coal Association, "Modern Dust Collection for Coal-Fired Industrial Boilers," NCA Fuel Engineering Data, Washington, D. C.

41. Hodason, John, "The Selection of Industrial Dust Collection Plant," Proceedings of Clean Air Conference (1965).

42. Yocom, J. E., and D. H. Wheeler, "How to Get the Most from Air-Pollution Control Systems," Chem. Eng., 127-136, June 1963.

43. Burdock, J. L., "Present Applications of Mechanical Collectors to Boilers," Proceedings of the 62nd Meeting of the Air Pollution Control Association, June 1969.

44. Op cit., Ref. 12.

45. Mau, G. A., "The Elimination of Dust from Asphalt Plants," Air Repair, 102-104, November 1953.

46. Gallaer, C. A., "Economics of Fly Ash Collection," Buell Engineering Company, New York, New York.

47. Air Engineering, 28-38, September 1964.

48. Sachsel, G. T., J. E. Yocom and T. A. Retzke, "Fume Control in a Fertilizer Plant - A Case History," JAPCA, **6**, 214-217, February 1957.

49. Dohrman, H. C., "Particle Size Analysis of Fly Ash," Buell Engineering Company, Lebanon, Pennsylvania.

50. Op cit., Sutton.

51. Newmann, E. P., C. R. Sederberg, and A. A. Fowle, "Design, Application, Performance and Limitations of Sonic Type Flocculators and Collectors," Ultrasonic Corporation, Cambridge, Massachusetts.

52. Burke, E., "Dust Arrestment in the Cement Industry," Chem. and Ind., 1312-1319, October 1955.

53. Peterson, A. A., "Fly Ash Collection for Small Plants," Meeting of the American Society of Mechanical Engineers, Washington, D. C., April 1950.

54. Larcombe, H. L. M., "Centrifugal Dust Collectors," The Mining Magazine, 137-148, September 1947.

55. Penick, Walter L., and Howard W. Lange, "Fifty Years of Dust and Fume Collection in the Mining Industry," Proceedings of the Ninth Pacific Northwest Industrial Dust Waste Conference, April 1959.

56. Henschen, H. C., "Wet vs. Dry Gas Cleaning in the Steel Industry," Journal APCA, 18, 338-342, 1968.

57. Wellet, H. P., and D. E. Pike, "The Venturi Scrubber for Cleaning Oxygen Steel Process Gases," Iron and Steel Engineer, pp. 126-131, July 1961.

58. Private communication, Mr. Al Brandt, Bethlehem Steel Corporation, January 1971.

59. Private communication, Mr. Jack Smith, Kaiser Steel Company, January 1971.

60. Person, R. A., "Control of Emissions from Ferroalloy Furnace Processing," Union Carbide Corporation, Niagara Falls, New York, 1969.

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APPENDIX A

PARTICULATE SAMPLING AND SIZING

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Summary

Standard stationary source sampling techniques are inadequate for collecting particles for accurate particle size determinations, particularly for particles 1 μ or smaller. Cyclone separators tend to break up aggregates and friable particles, stainless steel or alundum thimbles do not quantitatively capture the submicron particles, and small particles may penetrate deeply into the body of a fiber filtering medium before they are captured and then cannot be removed for subsequent analyses.

A sampling device which collects submicron particles and causes neither formation nor breakup of aggregates is necessary if accurate particle size information is to be obtained. Cascade impactors, thermal precipitators, and small electrostatic precipitators are devices that come close to meeting these requirements, and are clearly superior to the standard sampling trains. A cascade impactor which can be inserted inside a duct is the most versatile of these devices. Stainless steel cascade impactors are now available which permit "in-stack" collection of submicron particles.

The Bahco Micro-Particle Classifier has been used extensively for routine particle size measurements, and 95% of the data currently available on the particle size of particulates emitted from industrial sources have been obtained by using this device. The range of applicable particle diameter for the Bahco instrument is 5 to 60 μ. As a result of the extensive use of the Bahco method, only a meager quantity of accurate data is available on particle size in the < 2 μ size range.

1. Introduction

Measurements of the chemical and physical properties of particulate pollutants emitted from specific sources generally require a sample to be collected, i.e., the particulates must be separated out from the gas stream in which they exist. The process of sampling may change the physical properties of the individual particles and the size distribution of the particles. Following collection of the particulate, the desired physical and chemical measurements can be performed. Particulate pollutants, however, are not all alike and can be of different shapes and compositions. The variability in particulate properties has led to the development of numerous methods for the measurement of specific properties, such as particle size.

The selection of the method for determining the particle size or particle-size distribution of a given material is generally based on (1) the particle-size range, (2) the form in which results are desired (i.e., number-or-weight size curves), (3) application of the results, and (4) accuracy required. Different methods of determining the particle size may give quite different results, and the method used to prepare the samples for analysis can also be a deciding factor in what the analysis actually measures.

The limiting aspects of sampling methods and particle size analysis techniques assume added importance for the determination of the quantity of fine particulate emitted from specific sources. The applicability of standard sampling techniques and routine particle-sizing methods to the micron-or-less size regime is questionable. A discussion of conventional source sampling and particle-sizing methods and their ability to collect and measure fine particles is presented in the following sections.

2. Source Sampling Methods

The accurate collection of a representative sample from a flowing gas stream containing particulate matter is by no means a simple matter. In general, a representative sample can only be withdrawn from a flow if the probe through which it passes does not disturb the streamline pattern. Therefore, an ideal probe samples isokinetically and has infinitely thin walls. Both of these conditions are difficult to achieve in practice, and the problem is one of determining how far from the ideals one can depart and still obtain representative samples.

At the extremes of particle size, representative samples can be obtained despite disturbances caused by the presence of the probe and an anisokinetic sampling. Very small particles have low inertia and follow deflections of the streamlines with insignificant departure, and particles and gas are drawn into the probe in the correct proportions.

At the other extreme, very large particles, with relatively high inertia, enter the probe in straight trajectories independent of the streamline deflection, and the correct flow rate of particles is measured. When particles are about 10 μ, and the sampling velocity is lower than the velocity in the duct, some of the gases will be deflected around the probe. However, some of the particles, because of their inertia, will enter the probe and the sample will be biased toward the large particles. Conversely, if the sampling velocity is greater than the dust velocity, the sample will be biased toward the smaller particles.

An approximate guide to indicate when careful sampling is necessary can be obtained by using the dimensionless inertia parameter, ψ. This parameter, which is frequently used in deposition studies, is the ratio between the stopping distance of the particle and the diameter of the probe. The stopping distance, defined by Equation 1, is the distance the particle will travel when projected horizontally into a still atmosphere with velocity U .

$$\text{Stopping Distance} = \frac{\rho p d^2 UC}{18\ \mu_g} \tag{1}$$

where μ_g = viscosity of gas

ρ_p = density of particle

d = diameter of particle

U = stream velocity

C = Cunningham correction factor

Theoretical and experimental studies have shown that if ψ exceeds 50, the particles are not affected by the streamline deflection, and if ψ is less than 0.05 the particles follow the streamline closely.1/ Thus, isokinetic sampling is required if

$$0.05 < \frac{\rho d^2 UC}{18\ \mu_g D_p} < 50$$

where D_p = probe diameter.

A number of devices have been designed which nearly achieve isokinetic sampling. These devices either use a null-type sampling probe, or measure the velocity of the gas stream with a pitot tube as near to the probe as possible without interfering with the gas flow, and then adjusting the sampling velocity.[2,3] Since the velocity in a stack generally varies with distance from the wall, accurate sampling also requires the accumulation of samples from several different positions (i.e., traverse of the stack).

2.1 Sample Collectors

The usual method for collecting the particles from the gas-stream sampled by the probe is to draw the entire stream through a filter which is often in the form of a thimble. A small cyclone separator is also used in series with filters in some cases. Wet scrubbers have also been used in conjunction with cyclones.[4]

The standard collecting techniques are probably inadequate for collecting particles for accurate size determinations, particularly for particles in the micron or less size range. The cyclone separators will tend to break up aggregates and friable particles; stainless steel or alundum thimbles probably do not capture all or any of the submicron particles; and small particles may penetrate deep into the body of a fiber filtering medium before they are stopped. Particles which penetrate into the filters cannot be removed or observed microscopically. Another source of error in sampling aerosols for subsequent particle size analysis is leading the aerosol through a long and/or tortuous path before the particles are removed. The danger from this procedure is that particles are caught on the walls of the tubing, particularly near bends. Preferential trapping of certain particle sizes can produce serious errors in the particle size determinations.

A collection mechanism which collects submicron particles and causes neither a formation nor a break-up of aggregates is necessary if accurate size information is to be obtained. Small electrostatic precipitators, thermal precipitators, and cascade impactors are devices that come close to meeting these requirements.

2.2 Collector-Measuring Devices

2.2.1 Impaction devices: Impactor sampling devices are based on the fact than an aerosol particle suspended in a fluid stream tends to move in a straight line because of its inertia when the fluid flows around an obstacle. The larger particles, because of their greater mass, will have sufficient momentum to continue to move toward the object and impact on the surface. At the same time, particle motion relative to the gas stream is slowed by fluid resistance, and some particles may fail to reach the collector surface before they are carried past the sampler due to deflection in the fluid flow field. Impactors will provide meaningful results only under isokinetic sampling conditions.

Cascade impactors, constructed of stainless steel, are beginning to be used for "in-stack" source testing. Cascade impactors consist of a series of stages containing jets and collector plates. The jets in each stage through which the aerosol is drawn become progressively smaller. The particles are classified by inertial impaction according to their mass; the larger (heavier) ones are collected on the plate opposite the first stage, and the smallest (lightest) on the plate opposite the last stage. Figure A-1 illustrates a schematic of a source test cascade impactor.11/

The classification of particle size produced by impactors has certain advantages for microscopic determinations of size distributions when there is a large variation in particle size. Furthermore, this classification provides a technique for obtaining mass distribution curves, normally in the size range 0.3 to 60 μ. The impactor is calibrated to determine the smallest particles collected at each stage or, preferably, the size of particles which are sufficiently small that they are collected with only 50% efficiency at each stage. Size calibration is dependent upon the specific gas velocity through the instrument. Following calibration, the dust whose particle-size distribution is to be determined is then collected with the impactor. The weight of material collected at each stage is determined and the results are plotted as cumulative weight-distribution curves.4/

Impactors are capable of very high collection efficiency under rigid experimental conditions. An efficiency of 100% for particles as small as 0.6 μ has been obtained.4/ A commercial stainless steel eight-stage, multi-jet impactor for "in situ" stack sampling has recently become available, and is reported to be capable of sizing particles down to 0.1 μ.5/

Particle-size distributions determined by cascade impactors may be distorted by particle bounce, surface overloading (i.e., particle build-up and blow-off) and wall losses. Wall losses can be minimized by good impactor design and proper operation. Particle bounce may be reduced by using a viscous surface coating on the collector plates.

2.2.2 Thermal precipitators: Thermal precipitators have been used for many years in England and South Africa for ambient sampling. Thermal precipitators have also been used to a limited extent for stack sampling in this country.6-8/ The thermal precipitator makes use of a radiometer force produced by a thermal gradient between two different surfaces. Direct measurements of collection efficiency indicate that thermal precipitators

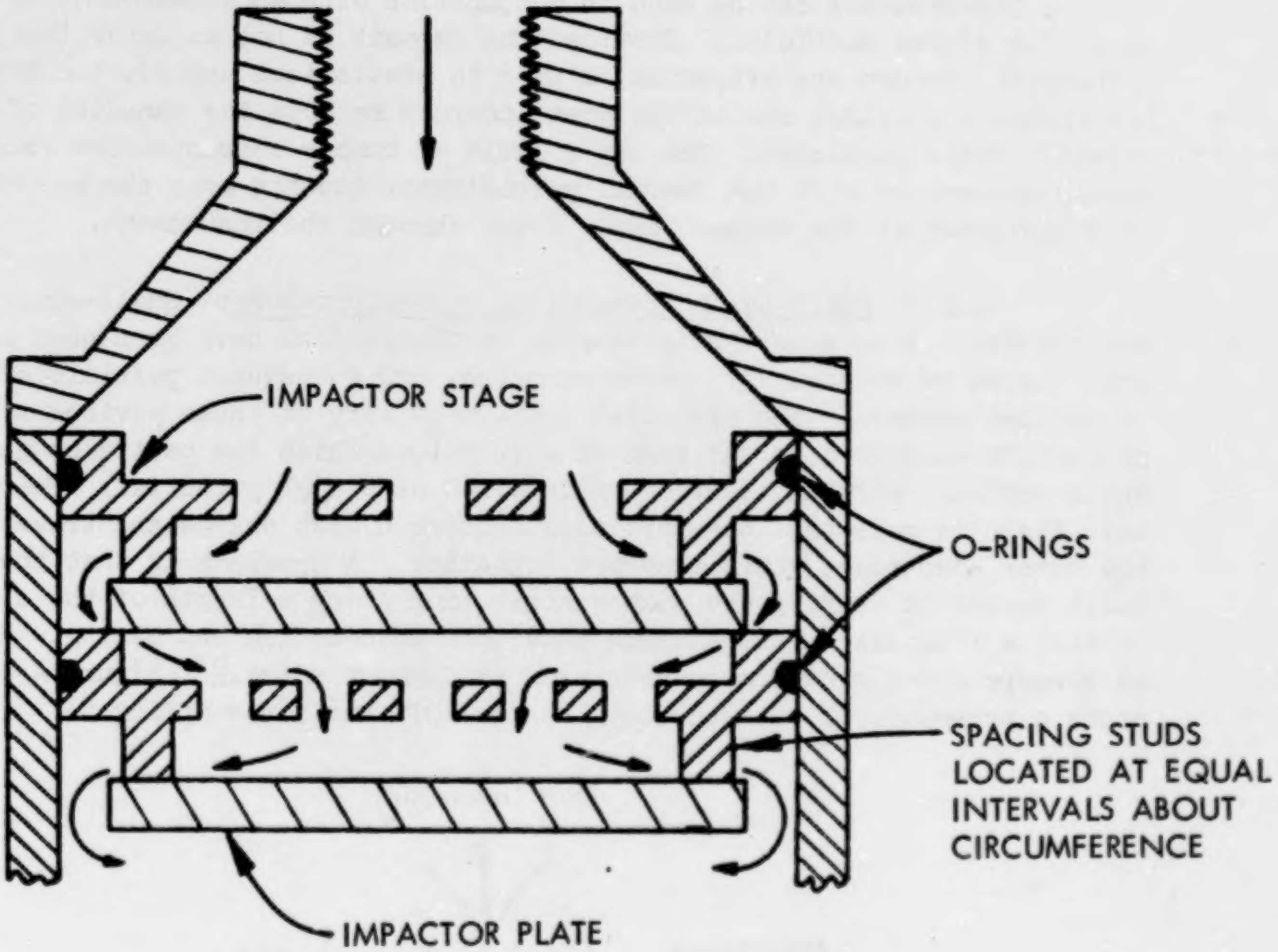

IMPACTOR STAGE
O-RINGS
SPACING STUDS LOCATED AT EQUAL INTERVALS ABOUT CIRCUMFERENCE
IMPACTOR PLATE

Figure A-1 - Schematic of Source Test Cascade Impactor11/

deposit virtually all particles of most materials from 5 down to 0.01 μ and possibly smaller. Figure A-2 illustrates the sampling head of a standard thermal precipitator.[9]

By depositing the particles on an electron microscope grid, the thermal precipitator can be used in conjunction with an electron microscope for sizing particles. Provided the deposit is not so dense that overlapping occurs and attention is paid to statistical errors, the thermal precipitator provides one of the most accurate methods for sampling of nonvolatile solid particles. The upper limit of number concentration which can be determined with the thermal precipitator depends upon the accuracy of measurement of the volume sample drawn through the instrument.

2.2.3 Small-scale electrostatic precipitators: Small-scale electrostatic precipitators in various configurations have been used with some degree of success for source sampling, and subsequent particle sizing by optical methods. The essential feature of many of these devices is a collecting electrode in the form of a tube down which the particles pass and a central ionizing electrode maintained at a high potential. The electric field is such that the particles acquire a high charge and travel to the outer electrode, where they are deposited. A drawback is that the deposit varies in density and size distribution along a length of the electrode so that a full assessment entails considerable counting and sizing. Electron microscope screens have also been used as deposit sites.[9] Figure A-3 presents a schematic of an electrostatic precipitator for sampling.[9]

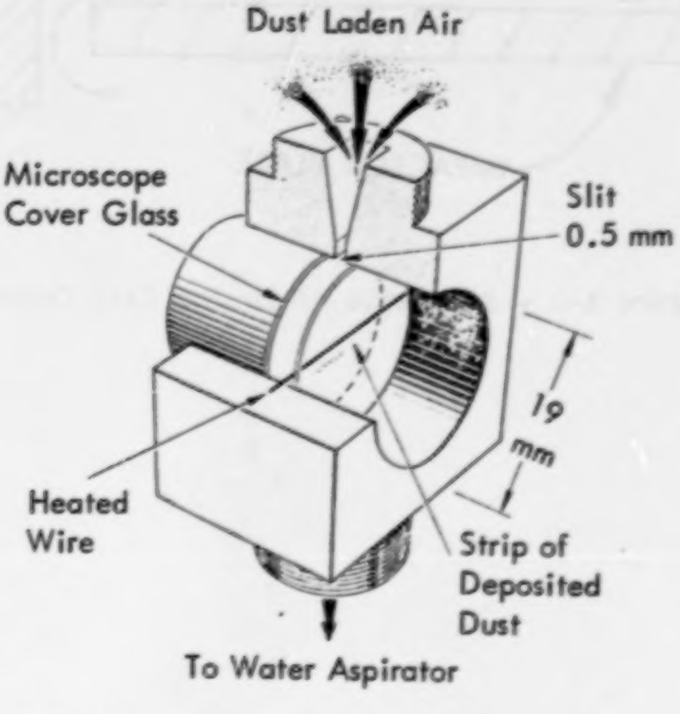


Figure A-2 - Sampling Head of Standard Thermal Precipitator[9]

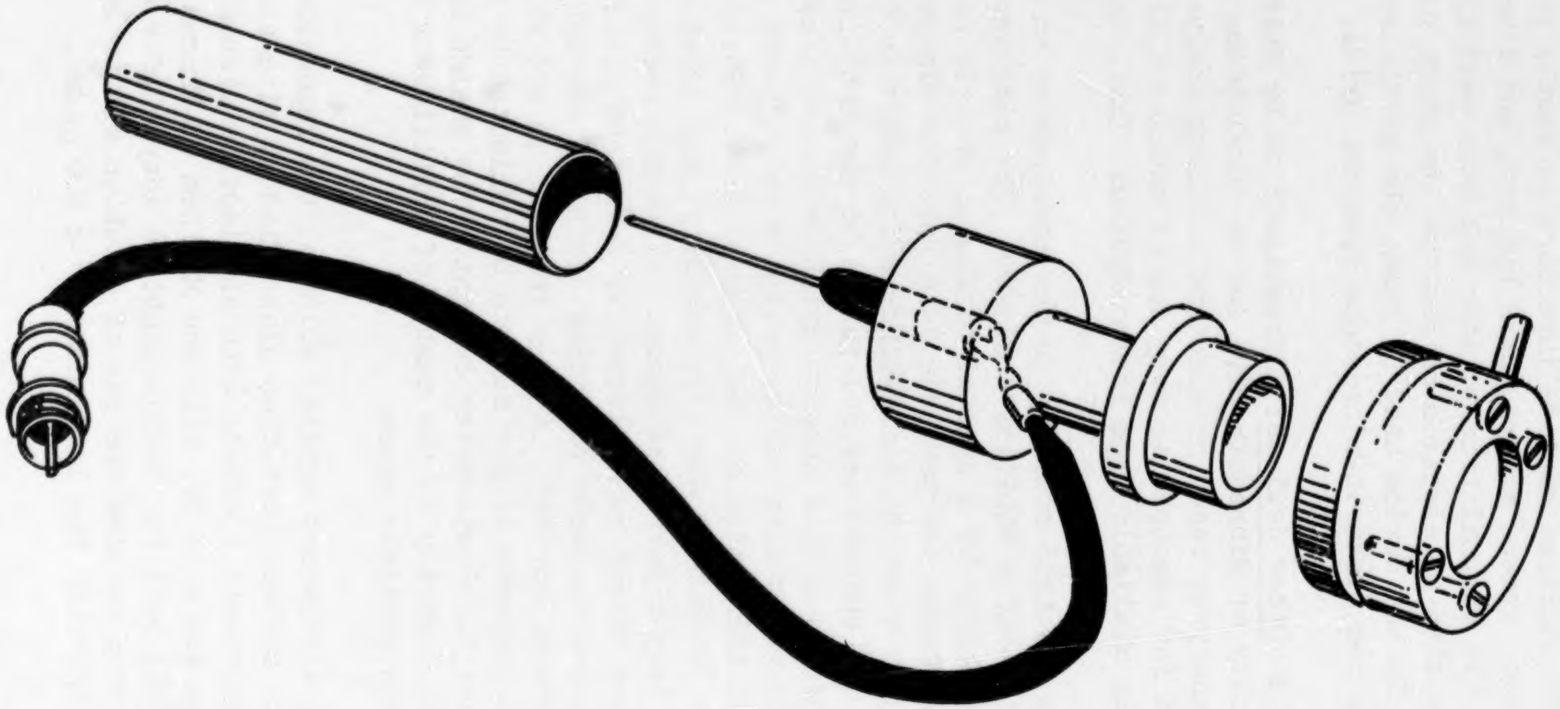


Figure A-3 - A Modified Electrostatic Precipitator Head with Collecting Electrode on the Left.

Impactors, thermal precipitators, and electrical precipitators are all capable of collecting particles in the submicron range. The cascade impactor is probably the most versatile of these devices for "in-stack" collection of submicron particles. Unfortunately, impactors have been used only to a limited extent.5/ Research groups at the University of Washington have utilized cascade impactors to sample pulp mill recovery furnaces, plywood veneer dryers, bark boilers, and aluminum reduction cells.11,12/ The thermal precipitator has been used by Bush and co-workers, in conjunction with an electron microscope, to study power plant stack discharges.6-8/ In the device used by Bush, the particles were thermally precipitated onto the electron-microscope specimen grids.

2.2.4 Other devices: Investigations by Whitby and co-workers at the University of Minnesota have led to development of a particle-size distribution analyzer based on electric mobility analysis. This instrument, designed for atmospheric sampling of submicron airborne particles, is commercially available from Thermo-Systems, Inc., in St. Paul, Minnesota.10/

This electric mobility device consists of an aerosol charging device and an electrical mobility analyzer. Entering aerosol is given a unipolar negative charge by a special diffusion charger (sonic-jet-diffusion-charger). The charge per particle is a reproducible function of the particle size and is a monotonically increasing function over the size range of interest. The charged aerosol passes to the mobility analyzer, where it is introduced as a thin annular cylinder around a core of clean air. A metal rod, to which a variable, positive voltage can be applied, passes axially through the center of the analyzer tube. Particles smaller than a certain size (with high electric mobility) are drawn to the collecting rod while the larger particles escape collection because of their lower mobility and are therefore collected by a current collecting filter. The electrical charges on these particles drain off through an electrometer, giving a measure of current. A step increase in rod voltage will cause particles of a discrete larger size to be collected by the rod with a resulting decrease in electrometer current. The change in electrometer current is related directly to the number of particles in the aerosol between the two discrete particle sizes.

With a constant applied voltage, the removable collector rod may also be used to collect particles classified by size along the length of the rod for subsequent analysis with an electron microscope. Discussions with Dr. Whitby and with Dr. Olin and Mr. Sem of Thermo-Systems indicate that the electric mobility device might be adapted for use in stack sampling. This would require the use of dilution air to decrease the mass concentration entering the instrument to $< 500\ \mu g/m^3$.

The recently developed method of laser holography offers a potential for remote particle size analysis. Hologram systems have recently been designed and used for recording and reconstructing relatively large volumes of particles in the size range from 3 to 1,000 μ mean diameter.[17-19]

3. Particle Size Measurement

Following collection of a particulate sample, a method of particle size determination must be selected. With the standard sampling techniques utilizing filters as collectors, redispersion of the collected particles is a potential problem. The methods used to prepare the samples for analysis can be the deciding factor in what the selected analysis method actually measures. Utilization of cascade impactors, thermal precipitators, or electrical precipitators minimizes this troublesome factor as optical techniques are generally used in conjunction with these devices.

Determination of particle size cannot be unique except for the special case of spherical particles. For irregular dust particles, the average dimension along three mutually perpendicular axes may be used, or the diameter of a sphere having the same volume or the same surface area as the particle may be chosen. Obviously, the more irregular the shape of the particles, the greater will be the variations in equivalent diameters. For extremely irregular particles like plates, rods, or stars, some other measure, such as specific surface or settling rate, will usually be more significant. In many gas-cleaning processes the settling velocity has direct physical meaning, independent of particle structure, and is preferred to equivalent diameter.

Because of the wide variations in particle shapes and sizes, no universal method or apparatus for particle size determination is possible even in principle. Table A-1 summarizes the type and character of size-discriminating properties that have served as the basis for particle size analysis, as well as classes of measurement techniques.[13] Each size analysis method depends on some property or combination of properties to distinguish one size from another. Table A-2 presents examples of devices common to each class, and the range of particle size for which each technique is likely to be applicable. References 3, 4, and 14 present extensive discussions of particle size analysis and analyzers, and the reader interested in more details is directed to these sources.

3.1 Current Practice in Industry

A major portion of the data currently available on the particle size of particulates emitted from industrial sources has been obtained by using the Bahco Micro-Particle Classifier. The Coulter Counter, Whitby Centrifuge/MSA Sedimentation, and microscopic techniques have also been

TABLE A-1

SHORT SUMMARY OF ANALYSIS TECHNIQUES[13/]

Size-Discriminating Property Type	 Character	Types of Measurement Technique
Geometric	Physical barrier	Sieving Ultrafiltration
Mechanical or Dynamic (in fluids)	Inertia	Impaction on surface Pressure pulse (sonic)
	Terminal settling velocity	Elutriation Sedimentation Decantation Photo-sedimentation
	Diffusion	Particle displacement Particle deposition
Optical	Imaging	Light microscopy Ultramicroscopy Electron microscopy
	Transmission	Spectrum
	Scattering	Single particle count Macroscopic
	Diffraction	Light X-ray Laser
Electrical	Resistance	Current alteration
	Capacitance	Potential pulse
	Charge	Tribo-charging Induction charging Corona charging
Magnetic	Magnetic particles	Particle migration; pulse
Thermal	Particle deposition	Particle migration
Physico-Chemical	Condensation	Growth of nuclei

TABLE A-2

SUMMARY OF TYPES OF SIZE-ANALYSIS TECHNIQUES

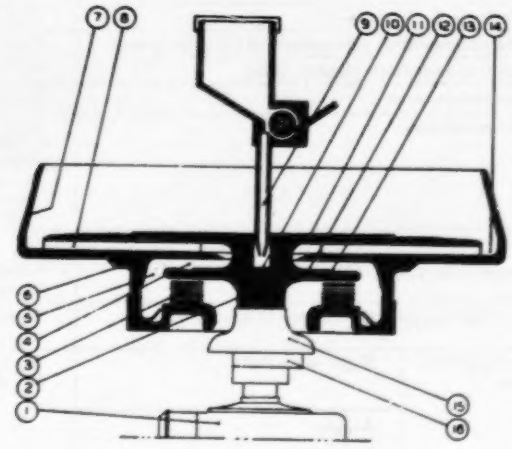
Size-discriminating Property		Technique and Variations			Example of Common Apparatus*	Range of Applicable Particle Diameter,* Microns
Type	Character or Mechanism					
Geometric	Physical barrier	Sieving	Wet		Ro-Tap (Tyler); Pulverit Shaker; Sonic Sifter (Allen-Bradley); electro-formed sieves (Buckbee Mears)	5-1000
			Dry			
		Ultrafiltration			Membranes, Millipore, Gelman	0.01-5
Mechanical or Dynamic (in fluids;	Inertia	Impaction on surface			Greenburg-Smith; May; Anderson; Cassella; Battelle	0.1-100
		Pressure pulse (sonic)			IITRI	10-1000(?)
	Terminal settling velocity (in gravity or centrifugal fields) (possibilities of using electrical fields exist)	Elutriation	Single fractionation	Liquid	Schöne	5-100
				Gas	Roller (G); Federal Pneumatic (C); Bahco (C)	
			Series fractionation	Liquid	Andrews	
				Gas	Houltain "Infrasizer"; Gonell; Aminco	
		Sedimentation	Layer methods (differential)	Liquid	Palo Travis (G); Werner (G); MSA-Whitby (G, C); Kaye (C)	1-100(G) 0.02-10(C) 0.002-1(UC)
				Gas	Micromerigraph (Sharples) (G); Conifuge (C)	
			Suspension methods	Differential-liquid	Pipette (Andreasen) (G); hydrometer (G); diver (G); Kamack (C); turbidimeter (G,C); differential manometer; gamma-ray absorption	
				Integral-liquid	Sedimentation balance (Oden, Cahn, Sartorius) (G); manometer (Weigner) (G); pendulum (G)	
				Integral-gas	Aerosol spectrometer (Goetz) (C); sedimentation channel (G)	
		Decantation (in liquid only)			Cummings	1-100(G)
		Photo-sedimentation (photography of particle streaks)			Carey & Stairmand	1-100(G)
	Diffusion	Particle displacement (random walk)			Millikan cell	0.01-1
		Particle deposition			Diffusion battery	
Optical	Imaging†	Light microscopy			American Optical; Bausch & Lomb; Leitz; Nikon Reichert; Tiyoda; Unitron; Vickers; Wild; Zeiss, etc. Flying-Spot counters	0.2-100
		Ultramicroscopy (gives mean size only)				0.005-1
		Electron microscopy			Hitachi; Norelco; RCA; Siemens	0.002-15
	Transmission (spectral)	Extinction measured as function of wavelength			Bailey	0.1-2(?)
	Scattering	Single particle count	Right angle (90°)		Royco counter (gas, liquid); O'Konski	0.2-50 (higher with microwave)
			Angular			
			Forward			
			Polarization		Owl (monodisperse aerosols)	
		Macroscopic (gives mean size only)			Sinclair-Phoenix (aerosol concentration)	
	Diffraction	Light				
		X-ray				
		Laser (holography-reconstruction of diffraction pattern)			Stat Volt Co.	
Electrical	Resistance	Alteration of current flow by particles			Coulter counter	1-100
	Capacitance	Potential pulse due to particle deposition				
	Charge	Tribo-charging			Guyton counter	1-30
		Induction charging				
		Corona charging			Drozin and LaMer; Mercer	
Magnetic	Applicable to magnetic materials only	Particle migration in magnetic fields; magnetic pulses				
Thermal	Particle deposition	Particle migration in thermal gradient			Cassella;	0.1-10(?)
Physico-chemical	Condensation	Growth of nuclei with controlled supersaturation			GE condensation nuclei counter	0.01-0.1(?)

* Items in parentheses have following significance: C = in centrifugal field; G = in gravity field; UC = ultracentrifuge.

† Replicas may be used in place of particles that might evaporate or be destroyed during measurement, e.g., in electron microscopy to avoid the effect of vacuum or electron beams, and in magnesium oxide film method for measuring size of drops

used. Cascade impactors, such as the Andersen and those developed by Pilat,[11,12] are just beginning to be introduced in routine stack sampling. Since in this program nearly all the data used to estimate fine particle emissions were obtained by one of the above methods, the capabilities of each method will be discussed in some detail.

3.1.1 Bahco classifier: The Bahco Micro-Particle Classifier is used extensively for routine measurements by control device manufacturing companies. The Bahco instrument is a combination air centrifuge-elutriator consisting of a brush feed system and a rotor assembly. The Bahco instrument separates a dry dust into nine fractions, according to terminal settling velocity. It does this by subjecting the particles to a centrifugal force, which is opposed by a current of air. The dust is thus divided into an elutriated or fine fraction and a settled or coarse fraction. By varying the air flow through the instrument, it is possible to change the particle size limit of division and thus the material can be divided into any number of fractions with limited particle size ranges. Eight throttles or air-orifice settings are used successively to permit the collection of nine fractions. If the weight and some measure of particle size of each dust fraction are known, a particle-size distribution curve can be plotted.[15] A simplified schematic diagram of a Bahco unit is shown in Figure A-4.[15]



1. Electric Motor
2. Threaded Spindle
3. Symmetrical Disc
4. Sifting Chm
4. Sifting Chamber
5. Container
6. Housing
7. Top Edge
8. Radial Vanes
9. Feed Point
10. Feed Hole
11. Rotor
12. Rotary Duct
13. Feed Slot
14. Fan Wheel Outlet
15. Grading Member
16. Throttle

Figure A-4 - Simplified Schematic Diagram of a Bahco-Type Micro-Particle Classifier Showing Its Major Components[15]

Failure to disperse the particles adequately as discrete particles is a major source of error with the Bahco instrument. Also, friable particulate matter may be broken by the analyzer and nonrepresentative size distributions will be obtained. Another common and inherent error in all elutriation techniques is that the fluid velocity is not constant across the ducts, so that the assumption of particle velocity equal to fluid velocity is usually invalid. In addition, the fractions obtained from elutriation do not have a sharp size distribution, so that average, estimated sizes have to be assigned. No quantitative measure is made of the amount of dust lost during transfer into and out of the instrument, but the loss can be minimized by careful handling. The range of applicable particle diameter for the Bahco instrument is 5 to 60 μ.

3.1.2 Coulter Counter: The Coulter Counter utilizes a change in electrolytic resistivity to determine particle size. The instrument determines a number-volume particle-size distribution of particles suspended in an electrically conductive liquid. The suspension flows through a small aperture having an immersed electrode on either side. The particle concentration is made low enough that the particles traverse the aperture one at a time in most cases.[16/] A simplified layout of the Coulter Counter is presented in Figure A-5.[16/]

Each particle passage displaces electrolyte within the aperture, momentarily changing the resistance between the electrodes and producing a voltage pulse, presumably proportional to particle volume. The resulting series of pulses is amplified, scaled, and counted using pulse-height analysis.

In order to have the Coulter Counter response proportional to size, a highly conducting medium is required, about 0.1 M electrolyte. In some instances this type of medium may interact with and/or solvate the particles and alter their size-to-voltage response ratio. Other potential sources of error are poor particle dispersion and the response of the instrument to physical-chemical properties of the particulate matter other than particle volume. The size range of applicability of this instrument is approximately 0.3 to 100 μ.

3.1.3 Differential sedimentation: The MSA-Whitby device is based on the differential layer sedimentation technique. Basic to the method are specially designed centrifuges that have speeds constant to within 1% and whose speed versus time curves during starting and stopping are known and constant enough so that corrections do not vary by more than ± 0.5 sec. Centrifuges of 300, 600, 1,200, 1,800 and 3,600 rpm whose starting and stopping characteristics are controlled by a combination of an inertia disk and a variable resistor in series with one winding of the motor have been developed. Special centrifuge tubes and a feeding chamber are employed.[16/]

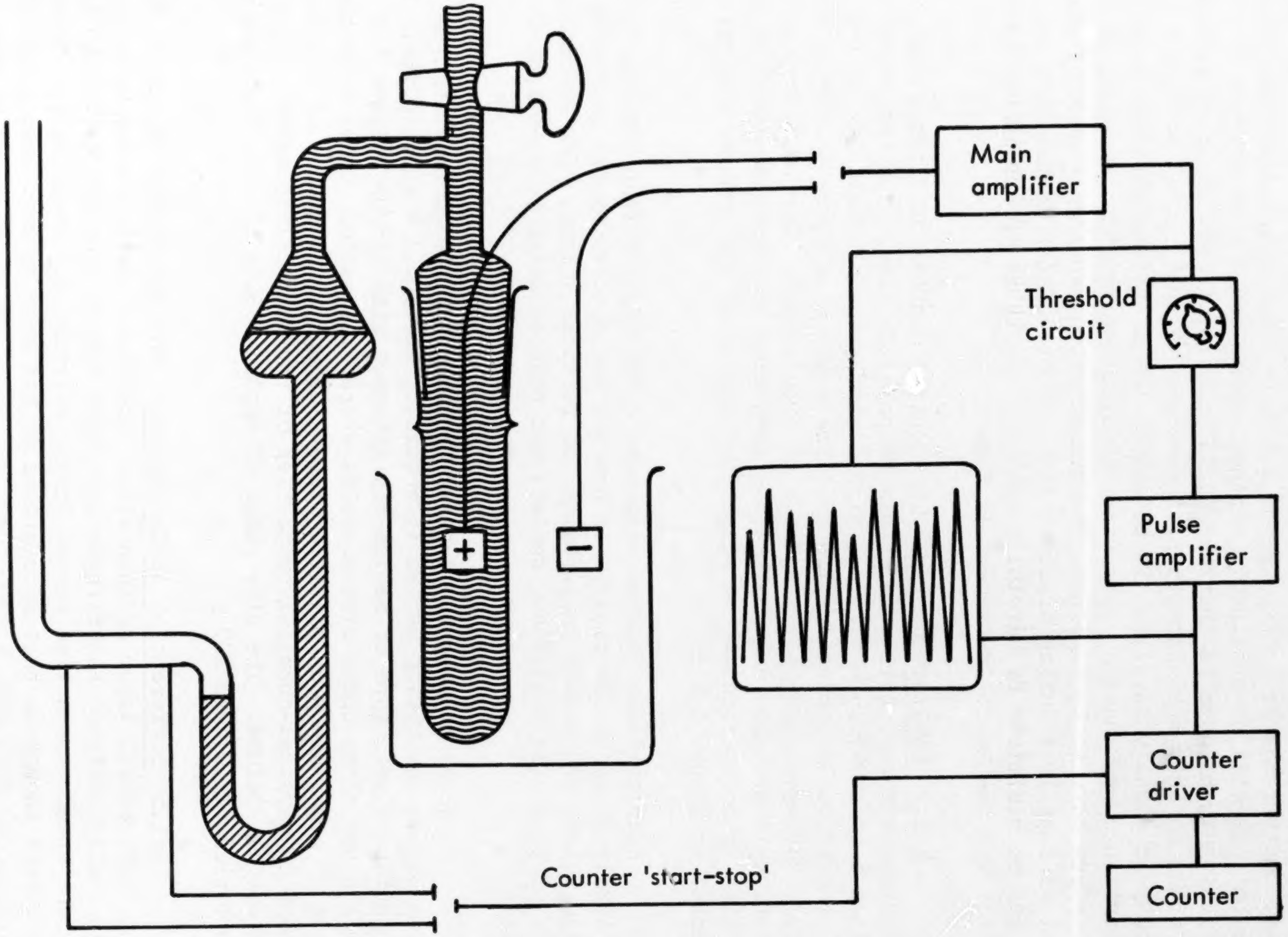

Main amplifier
Threshold circuit
Pulse amplifier
Counter driver
Counter
+
−
Counter 'start-stop'

Figure A-5 - Simplified Layout of the Coulter Counter16/

At the beginning of a size analysis, the clean tube is filled to the line near the top of the tube with a suitable sedimentation liquid (Figure A-6). Next a suspension of particles is made up in a liquid that is miscible with the sedimentation liquid but has a slightly lower density and a slightly higher viscosity, in order to minimize density streaming. An aliquot of this suspension is placed in a feeding chamber and then transferred to the sedimentation tube, leaving a sharp layer of suspension on top of the sedimentation liquid. Then, at the time calculated from Stokes' equation for desired sizes, the sediment height is read. When the particle-size distribution lies below 20 to 30 μ, the sedimentation tube is transferred to the lowest speed centrifuge and run for precalculated times, after which the sediment height is observed. The ratio of the sediment height at any time to the final height of sediment is assumed to give the fraction larger than the size calculated.

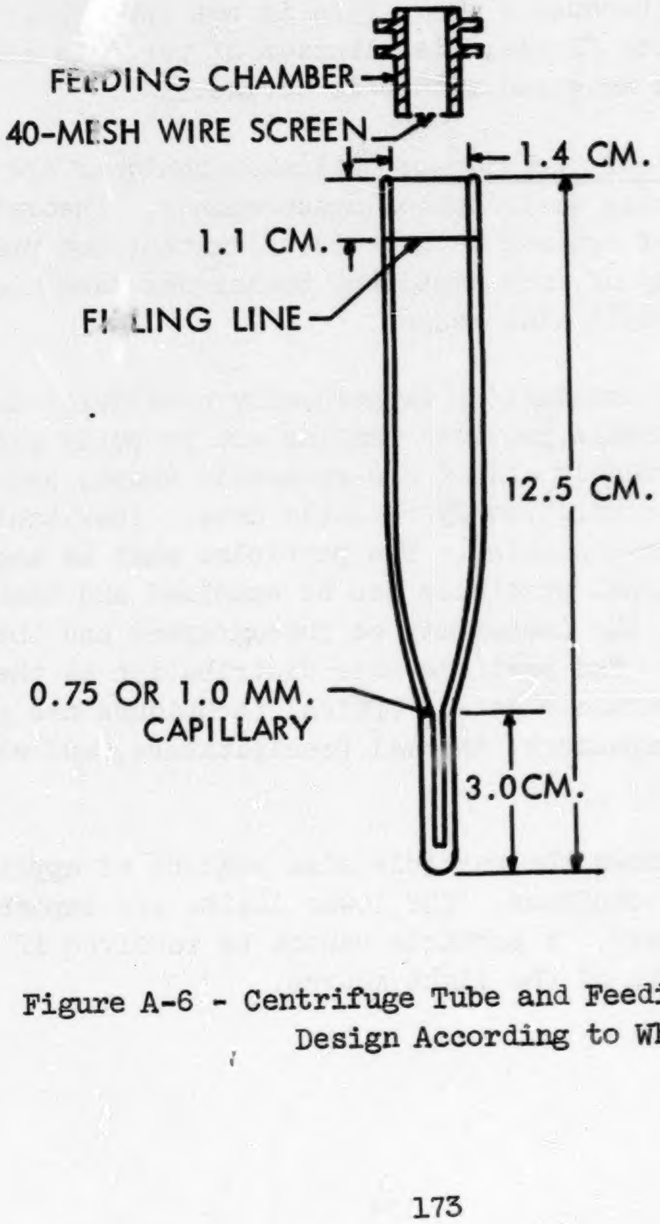


Figure A-6 - Centrifuge Tube and Feeding Chamber[16]
Design According to Whitby

Sediment height is assumed to be proportional to sediment weight. When complete dispersion of particulate matter is achieved, this is a good assumption, because one-size particles are essentially settling at one time, and the void space is independent of size for monodisperse systems. In many cases, however, strong aggregates of small particles exist; for example, 2-μ silica particles are aggregates of 0.01 to 0.03 ultimate particles. In these cases, compression of the sediment column with increasing centrifuge speed takes place, and bulk density correction factors must be used.16/

Another complication with this device is that no temperature control is provided, so that data obtained in non-air-conditioned laboratories are suspect. When a material having a narrow size distribution is studied, many particles may enter the capillary at the same time, causing plugging. Although a tapper is provided to minimize plugging and surface diffusion after settling, it disturbs sedimentation. In some cases involving transparent particles, serious difficulty may arise in deciding where to read the sediment height, because a sharp line is not apparent. With proper choice of sedimentation fluids, distribution of particle sizes in the range of 0.1 to 80 μ can be measured with this device.16/

3.1.4 Optical techniques: Optical techniques are the most direct method for particle-size distribution measurements. Theoretically, the applicability range of optical methods is unlimited; but practical limitations and availability of more expedient techniques make microscopy a less desirable tool in certain size ranges.

Microscopic examination is generally considered most reliable for particle size analysis provided samples are properly prepared, the particles are all or nearly all of one geometric shape, and enough of them are measured to give statistically reliable data. Inevitably, these methods are difficult and time-consuming. The particles must be magnified to such an extent that individual particles can be examined and their dimensions measured. Of course, the images may be photographed and the analysis made from the photographs. The particle-size distribution is then determined from the individual particle data. Optical techniques are generally used in conjunction with impactors, thermal precipitators, and electrostatic precipitators.

Table A-3 shows the particle size regions of applicability of several microscopic techniques. The lower limits are imposed by the attainable resolving power. A particle cannot be resolved if its size is close to the wavelength of the light source.

TABLE A-3

RANGE OF APPLICABILITY OF MICROSCOPIC TECHNIQUES

Method	Normal Size Range (μ)
White light	0.4 - 100
Ultraviolet light	0.1 - 100
Ultramicroscopy	0.01 - 0.2
Electron microscope	0.001 - 5

The errors involved in the microscope method can be broadly grouped in four categories: technique of slide preparation including sampling, dispersion and mounting; the optical arrangements; technique of particle measurement including questions of aggregation, shape factor and choice of diameter; and counting procedures.

Significant results from light microscopic measurements depend, first, on depositing a representative sample on a substrate by one of the sampling methods or on redispersing the sample effectively when a mass of material has been collected, perhaps with a filter. If the particle collection method, perhaps impingement or thermal precipitation, produces a deposit on a glass slide, the particles can be measured directly, provided the deposit is not dense (i.e., minimal superposition). When the collection is on a membrane filter, measurements can be made directly if the filter is made transparent.

Extreme care must be taken to ensure that a representative portion of any bulk sample is selected for analysis and that no classification occurs during microscope-slide preparation procedures. One method commonly used to distribute fine particles over a slide is to disperse the particles by means of agitation in a nondissolving liquid containing, usually, a dispersion agent. Stirring is continued to avoid any settling of the larger particles. A drop of this suspension is placed on the microscope slide for measurement. Classification may occur on the slide as the liquid evaporates. In so doing, small particles tend to migrate to the liquid boundaries, while the larger ones stay in place. If this is the case, individual particle measurements may be made by passing through the center of the deposit and examining particles from one periphery to the other. Sometimes classification caused by liquid evaporation can be avoided by spreading the suspension as quickly as possible into a thin film. A proper concentration of the particle suspension can be obtained only by experience or the trial-and-error approach.

Because separating previously collected particles into discrete entities without actually producing particle disruption is often difficult, the dispersing or wetting agent must be carefully chosen and only sufficient agitation provided to achieve the required dispersion. Lists of agents for use with a number of materials have been prepared.[14,16] In some cases, when analyzing a mass of collected aerosol material, complete dispersion may not be desirable. What may really be desired is the degree of agglomeration that prevailed in the aerosol state. Direct sampling by precipitation on a slide is best for this purpose.

Under a microscope a particle is seen as a projected area whose dimensions depend on the orientation of the particle on the slide. In order to get consistent measurements of the profiles of irregularly sized particles it is essential to adopt certain conventions; in practice, the most suitable are:[14]

1. Martin's diameter, which is the length of a line intercepted by the profile boundary which approximately bisects the area of the profile. The line may be drawn in any direction, but must be maintained constant for all the profile measurements.

2. Feret's diameter--length between two tangents on opposite sides of the particle and perpendicular to the bottom of the microscope field.

3. The diameter of the circle whose area is equivalent to the projected area of the particle.

Most observers find it easier to use the equivalent circle method. To facilitate use of this method, a graticule, which has a series of circles of different diameter scribed on it, is placed in the microscope eyepiece.[14]

A real difficulty in size estimation arises with some precipitated materials and sintered powders in which the particulate may be aggregates which are unaffected by dispersing agents. Such aggregates may have a very open structure and extremely variable shape, together with a rather indefinite density depending on particle size. The density may vary from the true material density for the smallest particle to a quite low figure for the largest aggregates. In such cases an approximation must be made in order to obtain figures for the weight distribution. A suitable one might be to measure the equivalent circle diameter of the aggregates, but to use for each size group an estimated density based on the apparent closeness of packing in the aggregates or found from settling tests on individual aggregates.[14]

Many particulates emitted from industrial sources contain a high proportion of particles smaller than 0.5 μ in diameter, and for these very fine particles electron microscopy provides a direct means of measuring size and shape. The electron microscope is the ultimate tool used to reference submicron particles to the size parameter. It is the only means of obtaining a full-size analysis of extremely small samples containing particles in the size range 0.001 to 5 μ. As the instrument uses electron lens or objectives of very small numerical aperture, it has a large depth of focus, while its resolving power is many times greater than that of the visible light microscope.

Electron microscopy requires specialized techniques for specimen preparation and these require some consideration if the utility of the method is to be fully appreciated.[4,16] Selection of the proper technique for preparing for electron microscope measurements depends on the kind of information sought, the condition of the sample, and the physical properties of the particles, just as in light microscopy. Likewise, other problems encountered are those of securing a representative sample and getting it sufficiently dispersed for individual particles to be distinguished one from another.

Direct examination of the particles from an aerosol is possible if the particles are deposited directly on prepared specimen grids by means of thermal or electrical precipitation. Caution should be exercised here, for particle classification can inadvertently occur depending on the location of the grids. Several grids placed at various locations in these samplers should be exposed unless the aerosol is known to contain a narrow particle size range.

Because of the very small field of view available and the consequently large number of plate exposures which must be made in order to count sufficient particles for an accurate analysis, electron microscopy is not suitable for routine analysis. However, the method is invaluable as a reference method when the time involved in specimen preparation may be justified.

REFERENCES

1. Parkes, G. J., "Some Factors Governing the Design of Probes for Sampling in Particle- and Drop-Laden Streams," Atmospheric Environment, Vol. 2, 477-490 (1968).

2. Strauss, W., Industrial Gas Cleaning, Pergamon Press, New York (1966).

3. Cadle, R. D., Particle Size - Theory and Industrial Applications, Reinhold Publishing Corporation, New York (1965).

4. Cadle, R. D., Particle Size Determination, Interscience Publishers, New York (1955).

5. Sales Brochure, "Andersen Air Samplers," 2000, Inc., South State Street, Salt Lake City, Utah.

6. Bush, A. F., and E. S. C. Bowler, "Electron Microscopy Studies of a Coal-Fired Steam Electric Generating Stack Discharge," Report No. S.I. 395, Department of Engineering, University of California, Los Angeles, California, December 1965.

7. Bush, A. F., and E. S. C. Bowler, "Electron Microscope Studies of a Bag Filterhouse Pilot Installation on a Coal-Fired Boiler," Report No. S.I. 405, Department of Engineering, University of California, Los Angeles, California, September 1966.

8. Bush, A. F., and E. S. C. Bowler, "Electron Microscopy Studies of a Steam Electric Generating Stack Discharges," Report No. C 60-79, S. I. 8007, Department of Engineering, University of California, Los Angeles, California (1960).

9. Green, H. L., and W. R. Lane, Particlulate Clouds: Dusts, Smokes, and Mists, 2nd Edition, D. Van Nostrand Company, Inc., Princeton, New Jersey (1964).

10. Flesch, J. P., "Calibration Studies of a New Submicron Aerosol Size Classifier," Journal of Colloid and Interface Science, **29** (3), 502-509 (1969).

11. Private communication, Prof. M. J. Pilat, University of Washington, Seattle, Washington, November 1970.

12. Bosch, J. C., "Size Distribution of Aerosols Emitted from a Kraft Mill Recovery Furnace," M. S. Thesis, University of Washington, Seattle, Washington (1969).

13. Lapple, C. E., "Particle-Size Analysis and Analyses," Chemical Engineering, 149-156, May 20, 1968.

14. Herdon, G., Small Particle Statistics, 2nd Edition, Butterworth's Scientific Publications, London (1960).

15. Sales Brochure, H. W. Dietert Company, Detroit, Michigan.

16. Irani, R. R., and C. F. Callis, Particle Size: Measurement, Interpretation, and Application, John Wiley, New York (1963).

17. Thomson, B. J., *et al.*, "Application of Hologram Techniques for Particle Size Analysis," Applied Optics, Vol. 6, No. 3, 519-526 (1967).

18. "Holographic Determination of Injected Limestone Distribution in Unit 10 of the Shawnee Power Plant," TRW Report 14103-6001-R0-00, June 1970 (Contract CPA 22-70-4).

19. "Investigation of Scattered Light Holography of Aerosols and Data Reduction Techniques," TRW Report 14103-6002-R0-000, November 1970 (Contract CPA 22-70-4).

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APPENDIX B

ADVERSE EFFECTS OF PARTICULATES ON HUMAN HEALTH

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Summary

The adverse effects caused by particulate matter on human health are, for the most part, related to injury to the surfaces of the respiratory system. Particulate material in the respiratory tract may produce injury itself, or it may act in conjunction with gases, altering their sites or their modes of action. A combination of particulates and gases may produce an effect that is greater than the sum of the effects caused by either individually (i.e., synergistic effect).

Laboratory studies of man and other animals show that the deposition, clearance, and retention of inhaled particles is a very complex process, which is only beginning to be understood. Particles cleared from the respiratory tract may exert effects elsewhere. Available data from laboratory experiments do not provide suitable quantitative relationships for establishing air quality criteria for particulates. These studies do, however, provide valuable information on some of the bio-environmental relationships that may be involved in the effects of particulate air pollution on human health.

Toxicological studies on animals have shown that:

1. Particulate matter may exert a toxic effect via one or more of three mechanisms:

    (a) The particle may be intrinsically toxic because of its inherent chemical and/or physical characteristics.

    (b) The particle may interfere with one or more of the clearance mechanisms in the respiratory tract.

    (c) The particle may act as a carrier of an adsorbed toxic substance.

2. Evaluation of irritant particulates on the basis of mass or concentration alone is not sufficient; data on particle size and number averages per unit volume of carrier gas are needed for adequate interpretation.

3. The toxicological importance to mankind of submicron particles cannot be overemphasized.

4. Particles below 1 μ may have a greater irritant potency than larger particles.

5. A small increase in concentration could produce a greater-than-linear increase in irritant response when the particles are < 1 μ.

6. All particulate matter does not potentiate the response to irritant gases.

7. Both solubility of sulfur dioxide in a droplet and catalytic oxidation to sulfuric acid play a role in the potentiation of sulfur dioxide by certain particulate matter.

The analyses of numerous epidemiological studies clearly indicate an association between air pollution, as measured by particulate matter accompanied by sulfur dioxide, and health effects of varying severity. This association is most firm for the short-term air pollution episodes. The studies concerned with increased mortality also show increased morbidity.

The association between long-term residence in a polluted area and chronic disease morbidity and mortality is somewhat more conjectural. However, in the absence of other explanations, the findings of increased morbidity and of increased death rates for selected causes, independent of economic status, must still be considered consequential.

Information is lacking regarding the mechanisms involved in the enhancement of viral virulence by specific air pollutants. Specific methods by which air pollutants can synergistically affect viral infections are unknown. It is possible that fine particulate matter may act as carriers for certain virus agents.

1. Introduction

The effects on man and his environment of particulate matter are produced by a combination of particulate and gaseous pollutants. The effects on human health are, for the most part, related to injury to the surfaces of the respiratory system. Such injury may be permanent or temporary. It may be confined to the surface, or it may extend beyond, sometimes producing functional or other alterations. Particulate material in the respiratory tract may produce injury itself, or it may act in conjunction with gases, altering their sites or their modes of action. A combination of particulates and gases may produce an effect that is greater than the sum of the effects caused by either individually (i.e., synergistic effect).

Laboratory studies of man and other animals show clearly that the deposition, clearance, and retention of inhaled particles is a very complex process, which is only beginning to be understood. Particles cleared from the respiratory tract may exert effects elsewhere. Available data from laboratory experiments do not provide suitable quantitative relationships for establishing air quality criteria for particulates. These studies do, however, provide valuable information on some of the bio-environmental relationships that may be involved in the effects of particulate air pollution on human health.

The following sections present an overview of (1) the physics and physiology of deposition, retention, and clearance in the respiratory system; (2) toxicological studies of atmospheric particulate matter; and (3) epidemiological studies of atmospheric particulate matter.

2. Deposition, Retention, and Clearance Processes in the Respiratory System

An understanding of the effect on human health of particulate pollutants requires knowledge of the following processes:

1. Mechanisms and efficiencies of particle deposition in the respiratory system;
2. Retention mechanisms;
3. Clearance mechanisms; and
4. Secondary relocation to other sites in the body.

Theoretical and experimental studies have been conducted to define the factors involved in deposition, retention and clearance processes. The principal results of these studies are summarized in the following sections.

2.1 Deposition

2.1.1 Theoretical aspects: The physical forces which operate to bring about aerosol deposition within the respiratory system vary in magnitude not only with particle size but also with the air velocities and times of transit of the air from place to place within the system and from moment to moment throughout the breathing cycle. Three mechanisms are of importance in the deposition of particulate matter in the respiratory tract:

1. Inertial impaction - greatest importance in deposition of large particles of high density, and at points in the respiratory system where the direction of flow changes at branching points in the airways;

2. Gravitational settling (sedimentation) - most important in the deposition of large particles or of high-density particles such as dusts of heavy metals; and

3. Diffusion (Brownian motion) - major mechanism for the deposition of small particles (below 0.1 μ) in the lower pulmonary tract.

The effectiveness with which the decomposition forces remove particles from the air at various sites depends upon the obstruction encountered, changes in direction of air flow, and the magnitude of particle displacement necessary to remove them from the air stream. The anatomical arrangement and physical dimensions of the respiratory system, transport mechanisms, flow rates and gas mixing, and aerosol particle size are important factors that must be considered in any physical analysis of the deposition of inhaled aerosols.

The Task Group on Lung Dynamics has recently developed a model for the deposition of particles in the respiratory tract.[2] Findeisen's anatomical model[3] was chosen as the basis for the Task Group Model. The Task Group used the conventional division of the respiratory tract into three compartments (nasopharyngeal, tracheo-bronchial, and pulmonary), and made three fundamental assumptions in the development of their model. These were:[2]

1. Log-normal frequency distribution is generally applicable to particle sizes in the atmosphere.

2. The physical activity of the individual affects deposition primarily by its action on ventilation.

3. The aerodynamic properties of the particle, the physiology of respiration, and the anatomy of the respiratory tract provide a basis for a meaningful and reliable deposition model.

Calculations, basically similar to those of Findeisen, were used to estimate the deposition in the three respiratory compartments. When the mass median aerodynamic diameters of 0.01 to 100 μ of various distributions were plotted against the estimated mass deposition of particles occurring in each respiratory compartment, surprisingly little variability was seen. The geometric standard deviation for these distributions varied from 1.2 to 4.5. The results of these calculations are shown in Figure B-1.[2] The curves indicate a relationship between the mass median aerodynamic diameter and the gravimetric fraction of the inhaled particles which would be deposited in each anatomical compartment. Within these limits (0.01 to 100 μ), the mass median aerodynamic diameter served to characterize the deposition probabilities of the entire particle size distribution. Other parametric functions of the particle distribution failed to produce such simple cohesive relationships.[1,2] Figures B-2 and B-3 present plots of the mass median diameter versus mean respiratory performance. The deposition in the tracheo-bronchial compartment is considered as constant at approximately 8% of the respired particulate matter.

2.1.2 Experimental studies: Experimental studies of the deposition of inhaled particulate material may be divided into two broad categories. The first group deals with the measurement of total deposition in the respiratory tract, and the second group is concerned with regional deposition within the various areas of the respiratory tract. Details of these experiments are given in Refs. 1 and 4. The following points can be made with respect to the overall retention characteristics of the respiratory system:[4]

1. Percentage deposition increases with aerodynamic particle size from a minimum value of about 25% at approximately 0.5 μ and approaches 100% for particles > 5 μ. Particles of different densities and shapes follow the same deposition curve when size is expressed in terms of equivalent diameter of unit-density spheres.

2. Percentage deposition also increases as particle size decreases below 0.5 μ owing to the increasing magnitude of the force of deposition by diffusion. For particles < 0.1 μ, the percentage deposited out of the total respired air approaches, in value, the fraction of tidal volume which reaches the pulmonary air spaces. This fact suggests that the absolute efficiency of alveolar deposition of these submicron particles approaches 100%.

3. Particles of hygroscopic materials are removed in higher percentages than are nonhygroscopic particles of the same (dry) size because of the growth of such particles by water adsorption from the moist air in the respiratory system.

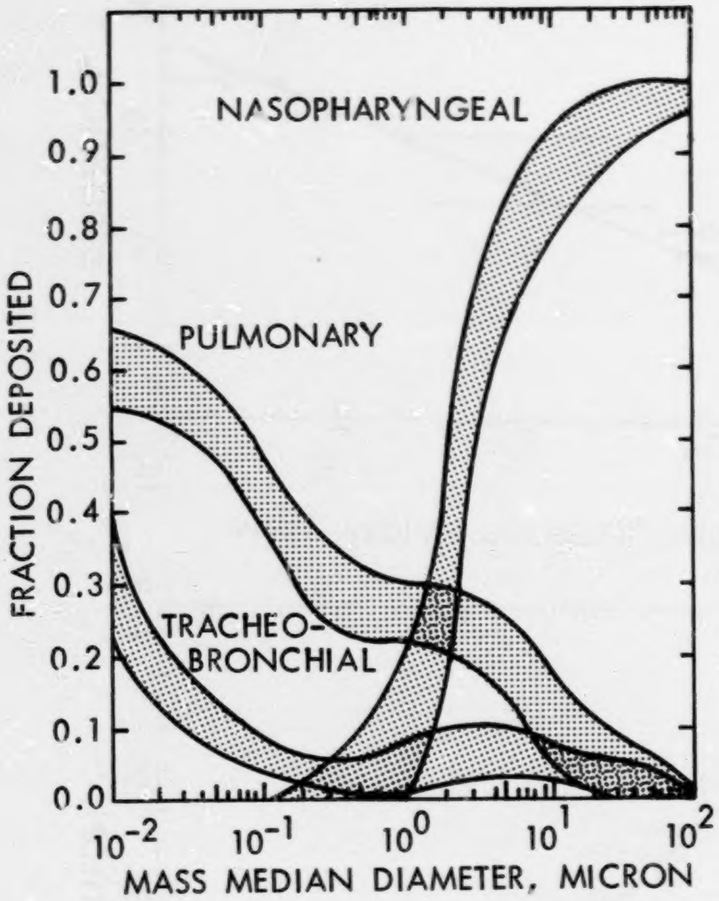

Figure B-1 - Fraction of Particles Deposited in the Three Respiratory Tract Compartments as a Function of Particle Diameter[2]

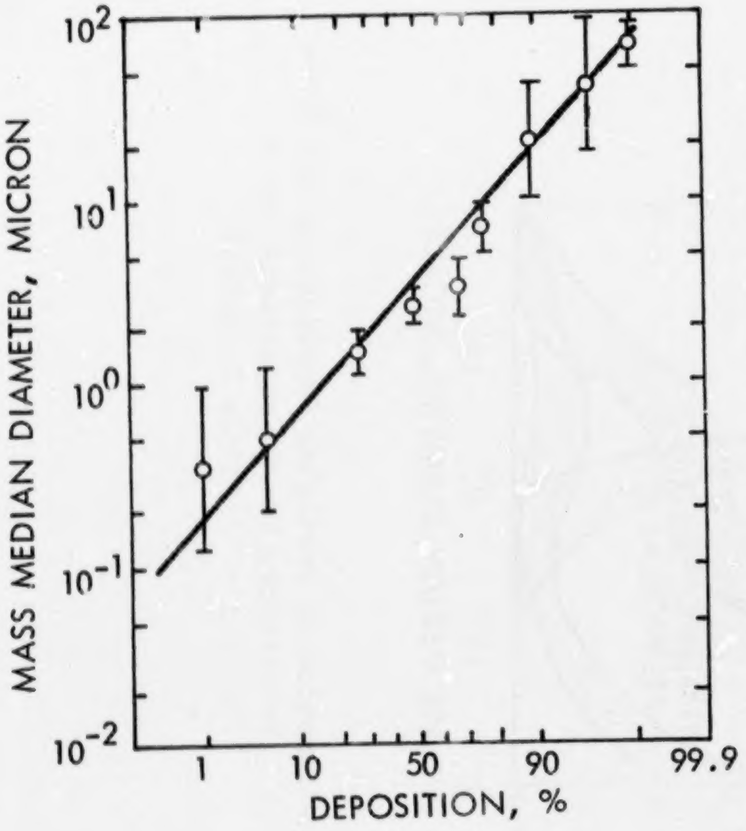

Figure B-2 - Data for the Nasopharyngeal Compartment Plotted as a Log-Probability Function (minute volume: 20 liters/min)[2]

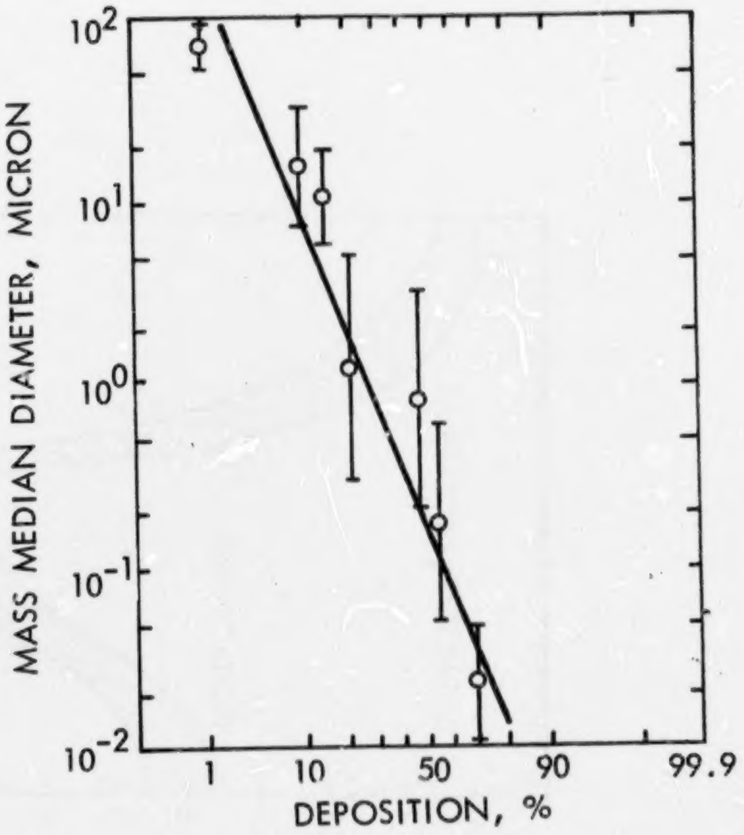

Figure B-3 - Data for the Pulmonary Compartment Plotted as a Log-Probability Function (minute volume: 20 liters/min)[2]

4. Percentage deposition varies with breathing frequency, increasing, for a heterogeneous aerosol, in both directions from a minimum level at frequencies of 15 to 20 cycles/min. At slower rates, the probability of deposition by gravity settlement and diffusion goes up in proportion to the increase in transit time of the dust-laden air into and out of the lungs. With more rapid breathing, percentage deposition of the coarser particles increases because of the rise in force of inertial deposition with increasing air velocity.

5. There is reasonably good agreement between the directly measured values of overall deposition and the levels predicted from mathematical-physical equations, with respect to both particle size and dynamics of air flow into and out of the respiratory system. Thus, in its behavior as a dust-trapping device, the respiratory system appears to act very much like any other similar physical apparatus.

The differing characteristics of particle retention at various depths within the respiratory system may be summarized as follows:[4]

1. Particles larger than 10 μ are essentially all removed in the nasal chamber and therefore have little probability of penetrating to the lungs. Upper respiratory efficiency drops off as size decreases and becomes essentially zero at about 1 μ.

2. The efficiency of particle removal is high in the pulmonary air spaces, being essentially 100% down to around 2 μ. Below this size it falls off to a minimum at about 0.5 μ. It then increases again as the force of precipitation by diffusion increases with further reduction in size.

3. The percentage penetration of particles into the pulmonary air spaces rises from essentially zero at 10 μ to a maximum at and below 1 μ, where it equals the fraction of tidal air which reaches the lung.

4. Below 0.5 μ, the probability of deposition in the pulmonary air spaces rises in proportion to the increase in the force of precipitation by diffusion with decreasing size.

5. Relative amount deposited and the distribution of the collected particles in the respiratory system change with breathing frequency and tidal volume. Upper respiratory trapping increases as the rate of inspired air flow goes up with faster breathing frequency. Magnitude of deep-lung deposition increases with slow, deep breathing because of the larger fraction of tidal air which reaches the pulmonary spaces and the longer transit time of air into and out of the lungs.

2.2 Clearance of Particulate Matter from the Respiratory System

The overall effectiveness of clearance mechanisms in the lung is well documented by the finding that the actual amount of mineral dust found in the lungs of miners or city dwellers at autopsy is only a minor fraction of the total dust that must have been deposited there during their lives. The clearance of certain particles may be very slow, and the rate is dependent upon size, site of deposition, and chemical composition.

Relative to other factors, the importance of removal from the respiratory system of trapped particulate materials depends on the rate at which the material elicits a pathological or physiological response. The effect of an irritant substance which produces a rapid response may depend more on the amount of initial trapping than on the rate of clearance. On the other hand, materials such as carcinogens, which may produce a harmful effect only after long periods of exposure, may exhibit activity only if the relative rates of clearance and deposition are such that a sufficient concentration of material remains in the body long enough to cause pathological change. In such a case, the amount of initial deposition will be of relatively minor importance.1/

Different clearance mechanisms operate in the different portions of the respiratory tract, so that the rate of clearance of a particle will depend not only on its physical and chemical properties such as shape and size, but also on the site of initial deposition. The fast phases of the lung clearance mechanisms are different in ciliated and nonciliated regions. In ciliated regions, a flow of mucus transports the particles to the entrance of the gastrointestinal tract, while in the nonciliated pulmonary region, phagocytosis by macrophages can transfer particles to the ciliated region. The rate of clearance is an important factor in determining toxic responses, especially for slow-acting toxicants such as carcinogens. The presence of a nonparticulate irritant or the coexistence of a disease state in the lungs may interfere with the efficiency of clearance mechanisms and thus prolong the residence time of particulate material in a given area of the respiratory tract. In addition, since the clearance of particles from the respiratory system primarily leads to their entrance into the gastrointestinal system, organs remote from the deposition site may be affected.1/

The Task Group on Lung Dynamics developed a model for respiratory clearance and also summarized experimental work on clearance. Details of the model and the analysis of experimental data are presented in Refs. 1 and 2, and the reader interested in a more complete discussion of respiratory clearance is directed to these sources.

3. Toxicological Studies of Atmospheric Particulate Matter

Experimental toxicology develops information on the mode of action of specific pollutants, on the relative potency of pollutants having a similar mode of action, and on the effect of one pollutant on the magnitude of response to another. If man could be used as the experimental subject, experimental toxicology would be the best means of deriving air quality criteria. However, the impossibility of performing experiments using human exposures to varying concentrations of a wide range of compounds precludes this direct approach. A limited amount of intentional human experimentation has been conducted, but most of the data for human toxicology are derived from accidental or occupational exposures.

The use of laboratory animals in toxicological experiments is more straightforward, but the obvious anatomical and metabolic differences between the animals and man require the exercise of caution in applying the results of animal exposures to human health criteria. Furthermore, many of the animal experiments have been conducted at exposure concentrations far in excess of those likely to be found in the atmosphere.

In spite of these limitations, toxicological studies have shown that atmospheric particles may elict a pathological or physiological response. Three types of responses have been determined:

1. The particle may be intrinsically toxic;

2. The presence of an inert particle in the respiratory tract may interfere with the clearance of other airborne toxic materials; and

3. The particle may act as a carrier of toxic material.

Few common atmospheric particulate pollutants appear to be intrinsically toxic; of these, the most important toxic aerosol is sulfur trioxide (SO_3) (either as the free oxide, or hydrated as sulfuric acid--H_2SO_4), which has a high degree of toxicity, at least for the guinea pig. Although silica (from fly ash) is frequently present as a pollutant, atmospheric concentrations are normally too low to lead to silicosis. In recent years, however, concern has been expressed over a number of less common toxic particulate pollutants, including lead, beryllium, and asbestos.

Toxic substances may be adsorbed on the surface of particulate matter, which may then carry the toxic principle into the respiratory system. The presence of carbon or soot as a common particulate pollutant is noteworthy, as carbon is well known as an efficient adsorber of a wide range of organic and inorganic compounds.

The role played by the affinity for the adsorbate by the particle is complex. A high affinity will mean that relatively large loads of adsorbate may be carried by each particle. If the adsorbate in its free state is slowly removed from the air in the respiratory system, then the deposition of particles carrying high concentrations may constitute a greater toxic hazard, especially at the localized deposition points. Whether or not the effect is significant depends on whether the efficiency of the desorption and elution processes is greater or less than that of the clearance process. The chemical nature of both adsorber and adsorbate, and the size of the adsorbing particle, all play a part in determining these various efficiencies, and each system will show its own individual characteristics.

3.1 Toxicological Studies of Specific Particulate Materials

Certain particulate materials are pulmonary irritants, and have been shown to produce alterations in the mechanical behavior of the lungs; the alteration is predominantly an increase in flow resistance. This was demonstrated by Amdur for sulfuric acid,[7] and by Amdur and Corn[5] for ammonium sulfate, zinc sulfate, and zinc ammonium sulfate, using the guinea pig as an assay animal. Nader and co-workers report a correlation between the alterations in pulmonary mechanics and actual anatomical change in cats exposed to aerosols of histamine and zinc ammonium sulfate.[8]

The effect of various aerosols on the response to SO_2 has also been also examined, using the guinea pig bioassay system. These data are presented in detail in Ref. 9. Conditions which lead to the solution of SO_2 in a droplet and catalyze its oxidation can alter the irritant potency of levels of SO_2 which occur in areas of high pollution. The concentration of the catalytic aerosols (soluble salts of iron, manganese, and vanadium) was of the order of 1 mg/m^3 which is higher than concentrations reported for these metals in urban air. Particles which do not form liquid droplets, i.e., non-soluble salts such as iron oxide fume, carbon fly ash, open hearth dust, and manganese dioxide, did not show a potentiating effect.

Dautrebande and DuBois have reported constriction and increased airway resistance in isolated guinea pig lungs and in human subjects with a wide variety of supposedly inert particulates.[10] The relationship of their results to Amdur's work is not clear since Dautrebande's particle concentrations appear to be abnormally high.

When a substance is dispersed in the air in the form of particulate matter, a simple statement of its concentration is insufficient to define in meaningful terms its toxic potential. The size of the particles is also a prime factor in the overall biological impact of inhaled particulate material.

This point can be illustrated with data obtained by Amdur and Corn for an aerosol of zinc ammonium sulfate.5/ The investigation of this compound was undertaken because it had been identified as one of the substances present during the 1948 Donora fog.6/ Figure B-4 shows the response of guinea pigs to zinc ammonium sulfate at a constant concentration (about 1 mg/m^3), but of different particle sizes. Within the size range studied, the irritant potency increased with decreasing particle size. Figure B-5 shows the more extensive data obtained on the dose-response curves of zinc ammonium sulfate at different particle sizes. These data show that not only is the irritant effect greater for the smaller particles at a given concentration, but also the dose-response curve steepens as the particle size is decreased. Thus, if an irritant aerosol is composed of very small particles, a relatively slight increase in its concentration can produce a relatively great increase in irritant response.

From the analytical data6/ it can be estimated that the concentration of zinc ammonium sulfate present during the Donora fog might have been on the order of magnitude of 0.05 to 0.25 mg/m^3. The toxicological data can in no way be extrapolated to predict what, if any, contribution this substance made to the overall irritant character of the atmosphere. On the other hand, the data do indicate that without information on particle size, such predictions are not possible.

The possible influence of inert particulate matter on the toxicity of irritant gases has been the subject of considerable speculation and a limited amount of experimental work. Work on the synergistic effects of aerosols and irritant gases is reported in Refs. 11 to 19. The potentiation of irritant gases by particulate material noted in these studies was attributed to the adsorption of gas on the particles. Adsorption of the gas on small particles would tend to carry more gas to the lungs and thus increase the toxicity. Unfortunately in many of these studies, the end point was the dosage required to produce death. With concentrations of this magnitude, the results have little applicability to air pollution.

Amdur has studied the effect of particulate material on the response to sulfur dioxide using the pulmonary flow resistance technique. None of the aerosols used in the studies produced any effect alone.9/ From these studies it appears that the major mechanism underlying the potentiation is solubility of sulfur dioxide in a droplet and subsequent catalytic oxidation to sulfuric acid.

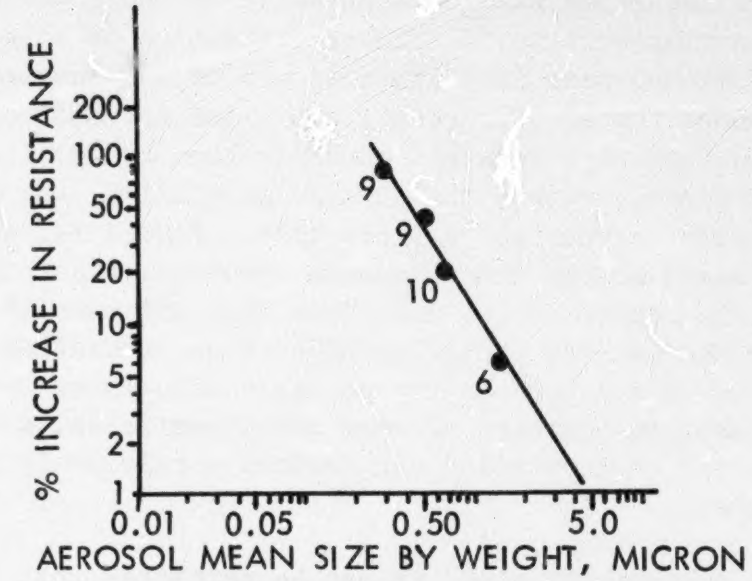

Figure B-4 - Effect of Particle Size on the Response to Approximately 1 mg/m^3 Zinc Ammonium Sulfate. Numbers beside each point indicate the number of animals.5/

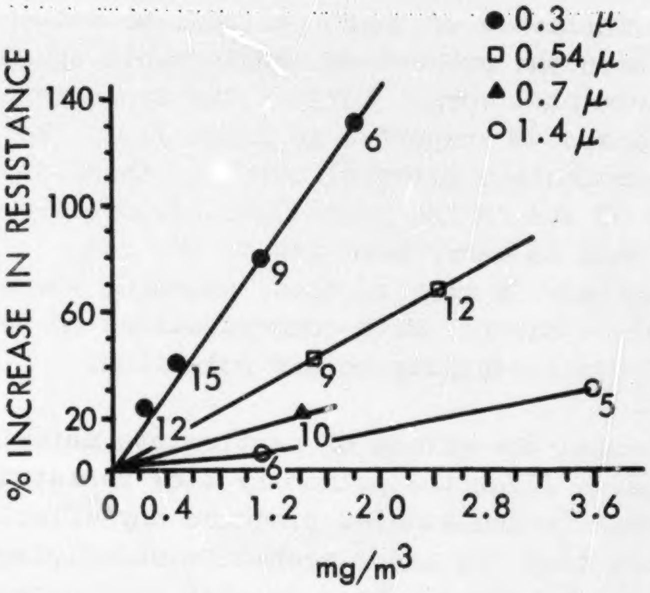

Figure B-5 - Relationship of Response to Concentration for Zinc Ammonium Sulfate of Different Particle Sizes. Numbers beside each point indicate the number of animals.5/

Figure B-6 shows the effect of aerosols of sodium chloride, potassium chloride, and ammonium thiocyanate, at concentrations of about 10 mg/m^3, on the response to about 2 ppm sulfur dioxide. All these substances are soluble salts which would absorb water to become liquid droplets at the humidity of the respiratory tract. Sulfur dioxide is increasingly soluble in aqueous solutions of these salts as one goes from sodium chloride, to potassium chloride, to ammonium thiocyanate. The degree of potentiation observed can be related in a reasonable manner to the degree of solubility of sulfur dioxide in the salt solutions.

Figure B-7 shows the results of exposure to about 2 ppm of sulfur dioxide alone and in the presence of another group of aerosols. These aerosols do not take on water to become droplets during transit of the respiratory tract, and have no detectable effect upon the response to sulfur dioxide. The combination of data in Figures B-6 and B-7 suggests that solubility in a droplet plays a role.[9]

Figure B-8 shows the dose-response curves to sulfur dioxide alone and in the presence of aerosols of soluble salts of manganese, iron, and vanadium. These substances were present at a concentration of about 1 mg/m^3. They have another property in common. When such salts become nuclei of fog droplets, they are capable of catalyzing the oxidation of sulfur dioxide to sulfuric acid.[20] The addition of these inert particles produced about a threefold potentiation in the response to sulfur dioxide. The similar magnitude of potentiation produced by the three salts suggests a similar mechanism for the potentiation. The data from Figure B-7 showing the lack of potentiation by dry manganese dioxide or iron oxide would appear to indicate the importance of solubility.

Experimental data on the effect of particulate matter on the responses to sulfur dioxide in human subjects are very limited.[21,25] Furthermore, there is no general agreement regarding potentiation by particulates. To date human exposures have been disappointing in disclosing mechanisms of interaction between various air pollutants. On the other hand, there is no evidence as yet for a species difference between animals and man; therefore, we may extrapolate judiciously to man from the animal studies.

Conclusions

1. Particulate matter may exert a toxic effect via one or more of three mechanisms:

(a) The particle may be intrinsically toxic because of its inherent chemical and/or physical characteristics.

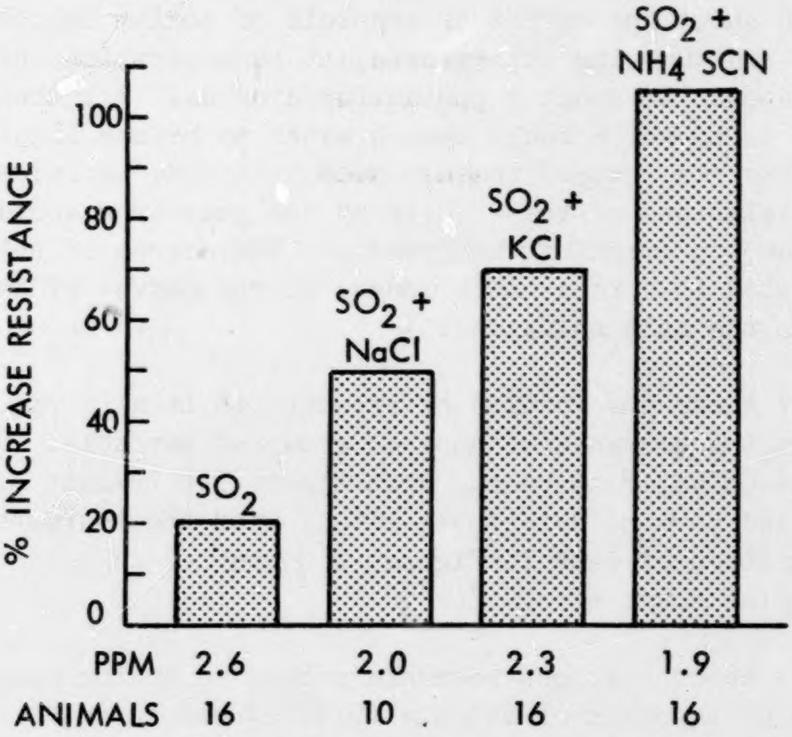

Figure B-6 - Effect of Aerosols Capable of Dissolving Differing Amounts of Sulfur Dioxide on the Irritant Potency of the Gas[8/]

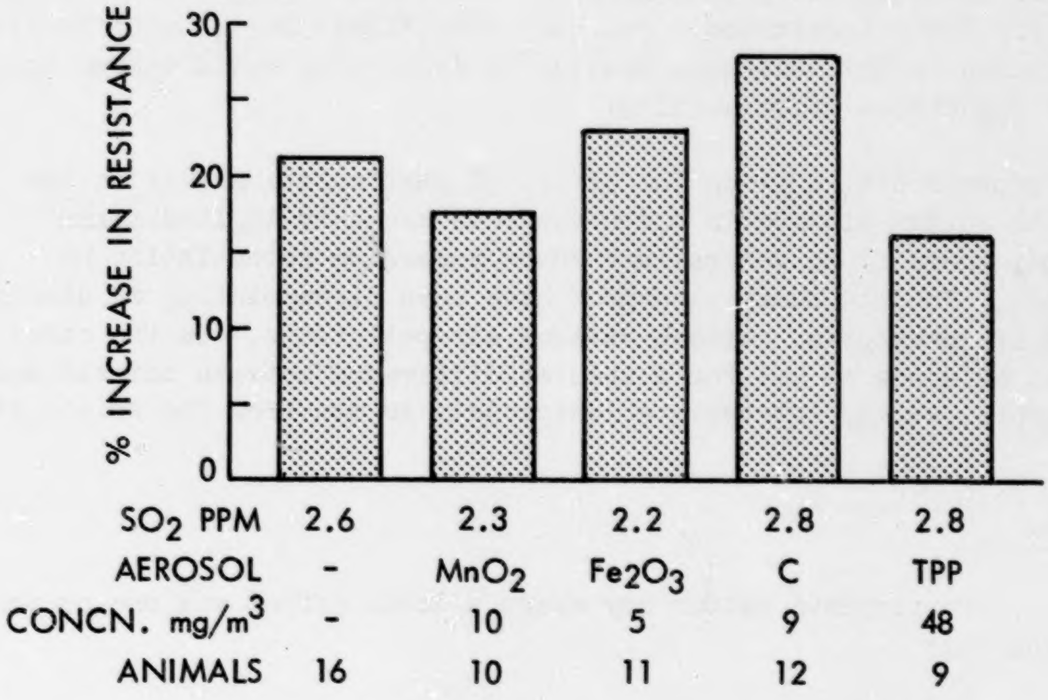

Figure B-7 - Response to Sulfur Dioxide Alone and in the Presence of Various Solid Aerosols[8/]

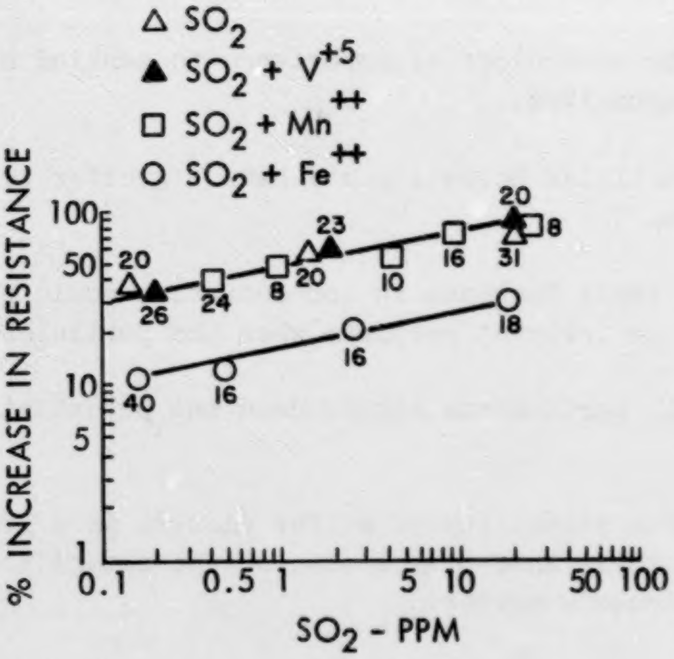

Figure B-8 - Effect of Aerosols Which Would Form Droplets and Also Catalyze the Oxidation of Sulfur Dioxide to Sulfuric Acid on the Irritant Potency of the Gas. The numbers beside each point indicate the number of animals.[8]

(b) The particle may interfere with one or more of the clearance mechanisms in the respiratory tract.

(c) The particle may act as a carrier of an adsorbed toxic substance.

2. Evaluation of irritant particulates on the basis of mass or concentration alone is not sufficient; data on particle size and number averages per unit volume of carrier gas are needed for adequate interpretation.

3. The toxicological importance to mankind of submicron particles cannot be overemphasized.

4. Particles below 1 µ may have a greater irritant potency than larger particles.

5. A small increase in concentration could produce a greater-than-linear increase in irritant response when the particles are < 1 µ.

6. All particulate matter does not potentiate the response to irritant gases.

7. Both solubility of sulfur dioxide in a droplet and catalytic oxidation to sulfuric acid play a role in the potentiation of sulfur dioxide by certain particulate matter.

4. Epidemiological Studies of Atmospheric Particulate Matter

The ultimate assessment of the impact of air pollution on human health can come only from epidemiology. Because particulate matter and sulfur oxides tend to occur together in a polluted atmosphere, few epidemiologic studies have been able adequately to differentiate the effects of the two pollutants. Because we do not now have a good epidemiological basis for stating the influence of particulates, only a brief synopsis of epidemiological studies of atmosphere particulate matter will be presented. References 1 and 26 present an extensive review of epidemiological studies, and those seeking more detail are directed to these sources.

Epidemiologic studies of the relationship between pollutant concentrations and their effects on health have used indices varying from disturbance of lung function to death. British studies of acute episodes of increased pollution show excess deaths occurring at smoke levels from 750 µg/m^3 to 2,000 µg/m^3. High SO_2 levels are, of course, concurrently present. The excesses of mortality are always accompanied by a very large increase in illness, mainly exacerbations of chronic conditions. Similar, but less spectacular, episodes have been reported in New York City.[1]

Winkelstein found in Buffalo that increases in the mortality rate were significantly linked to higher levels of suspended particulate pollution.[27] His studies showed that mortality from all causes, from chronic respiratory diseases, and from gastric carcinoma increased from the lowest of his five levels of pollution (less than 80 $\mu g/m^3$) through the three higher ranges, after the effects of socioeconomic status had been considered. Zeidberg found in Nashville significant increases in all respiratory deaths at soiling levels over 1.1 cohs annual average.[28,29] Neither of these studies took smoking habits into account, and the Nashville study only partially allowed for socioeconomic factors.

Studies of illness in relation to residence in more- and less-polluted areas contribute additional information. Fletcher et al. noted a proportional decline in the production of morning sputum in chronic bronchitics in West London from 1961 to 1966 as smoke pollution in their residence areas declined from 140 $\mu g/m^3$ annual mean.[30] Douglas and Waller found an increase in frequency and severity of lower respiratory illness at smoke and SO_2 levels over 130 $\mu g/m^3$ annual average.[31] A study of Lunn et al. shows similar differences occurring with more morbidity measured between about 100 $\mu g/m^3$ and 200 $\mu g/m^3$ of smoke, and for others between 200 $\mu g/m^3$ and 300 $\mu g/m^3$ annual average.[32]

Physiologic studies of lung function have also been made in both adults and children. On the basis of present limited knowledge it appears that the alterations found may be both temporary and permanent. The observations now available relate to long-term residence in a given area. The study reported in Ref. 32 shows reduced pulmonary function in the children in the most polluted area, i.e., where smoke concentration is above 300 $\mu g/m^3$. Studies in Japan show a decrease in pulmonary function in school children living in areas of high dustfall as compared with those living in low dustfall areas. In Osaka the dustfall levels were 6.5 gm/m^2-month and 13.3 gm/m^2-month.[33]

The analyses of numerous epidemiological studies clearly indicate an association between air pollution, as measured by particulate matter accompanied by sulfur dioxide, and health effects of varying severity. This association is most firm for the short-term air pollution episodes. The studies concerned with increased mortality also show increased morbidity.

The association between longer term community exposures to particulate matter and respiratory disease incidence and prevalence rates is believed to be intermediate in its reliability.[1]

The association between long-term residence in a polluted area and chronic disease morbidity and mortality is somewhat more conjectural. However, in the absence of other explanations, the findings of increased morbidity and of increased death rates for selected causes, independent of economic status, must still be considered consequential.

Information is also lacking regarding the mechanisms involved in the enhancement of viral virulence by specific air pollutants. Specific methods by which air pollutants can synergistically affect viral infections are unknown. It is possible that fine particulate matter may act as carriers for certain virus agents. Experimental evidence bearing on this point is lacking. The complex interrelationship between the dynamic inflammatory processes is difficult to define. So are the equally important irritative effects of air pollutants and viral infections.

REFERENCES

1. Air Quality Criteria for Particulate Matter, USDHEW, NAPCA Publication AP-49, Washington, D. C., January 1969.

2. "Deposition and Retention Models for Internal Dosimetry of the Human Respiratory Tract," Task Group on Lung Dynamics, Health Physics, 12, 173-207 (1966).

3. Findeisen, W., "Uber das Absetzen kleiner in der Luft suspendierten Teilchen in der menschlichen Lunge bei der Atmung," Arch. Ges. Physiol., Vol. 236, 367-379 (1935).

4. Hatch, T. F., and Paul Gross, Pulmonary Deposition and Retention of Inhaled Aerosols, Academic Press, New York (1964).

5. Amdur, Mary O., and Morton Corn, "The Irritant Potency of Zinc Ammonium Sulfate of Different Particle Sizes," Amer. Indust. Hyg. Assoc. Journal, 24, 326-333 (1963).

6. Hemeon, W. G. L., "The Estimation of Health Hazards from Air Pollution," Arch. Indust. Health, 11, 397-402 (1955).

7. Amdur, M. O., "The Respiratory Responses of Guinea Pigs to Sulfuric Acid Mist," Arch. Ind. Health, 18, 407-414 (1958).

8. Nader, J. A., et al., "Location and Mechanism of Airway Constriction after Inhalation of Histamine Aerosol and Inorganic Sulfate Aerosol," In: Inhaled Particles and Vapors, Vol. 11, C. N. Davies (ed.), Pergamon Press, London (1967).

9. Amdur, M. O., and D. Underhill, "The Effect of Various Aerosols on the Response of Guinea Pigs to Sulfur Dioxide," Arch. Environ. Health, 16, 460-468 (1968).

10. Dautrebande, L., Microaerosols, Academic Press, New York (1962).

11. Dautrebande, L., "Bases experimentales de la protection contre les gas de combat," J. Duculot (Belgium) (1939).

12. Dautrebande, L., and R. Capps, "Studies on Aerosols. IX. Enhancement of Irritating Effects of Various Substances in the Eye, Nose, and Throat by Particulate Matter and Liquid Aerosols in Connection with Pollution of the Atmosphere," Arch. Intern. Pharmacodyn, 82, 505-527 (1950).

13. Dautrebande, L., J. Shaver and R. Capps, "Studies on Aerosols. XI. Influence of Particulate Matter on Eye Irritation Produced by Volatile Irritants and Importance of Particle Size in Connection with Atmospheric Pollution," Arch. Intern. Pharmacodyn, 85, 17-48 (1951).

14. LaBelle, C. W., J. E. Long and E. E. Christofano, "Synergistic Effects of Aerosols. Particulates as Carriers of Toxic Vapors," Arch. Ind. Health, 11, 297-304 (1955).

15. Dalhamn, T., and L. Reid, "Ciliary Activity and Histologic Observations in the Trachea after Exposure to Ammonia and Carbon Particles," In: Inhaled Particles and Vapours, Vol. II, C. N. Davies (ed.), Pergamon Press, London (1967).

16. Boren, H. C., "Carbon as a Carrier Mechanism for Irritant Gases," Arch. Environ. Health, 8, 119-124 (1964).

17. Gross, P., W. E. Rinehard and R. T. DeTreville, "The Pulmonary Reactions to Toxic Gases," Am. Ind. Hyg. Assoc. J., 27, 315-321 (1967).

18. Pattle, R. E., and F. Burgess, "Toxic Effects of Mixtures of Sulphur Dioxide and Smoke with Air," J. Pathol. Bacteriol., 73, 411-419 (1957).

19. Salem, H., and H. Cullunbine, "Kerosene Smoke and Atmospheric Pollutants," Arch. Environ. Health, 2, 641-647 (1961).

20. Johnstone, H. F., and D. R. Coughanowr, "Absorption of Sulfur Dioxide in Air Oxidation in Drops Containing Dissolved Catalysts," Indust. Eng. Chem., 50, 1169-1172 (1958).

21. Frank, N. R., M. O. Amdur and J. L. Whittenberger, "A Comparison of the Acute Effects of SO_2 Administered Alone or in Combination with NaCl Particles on the Respiratory Mechanics of Healthy Adults," Intern. J. Air & Water Poll., 8, 125 (1964).

22. Burton, G. G., M. Corn, J. B. L. Gee, C. Vassallo and A. Thomas, "Absence of Synergistic Response to Inhaled Low Concentration Gas-Aerosol Mixtures in Healthy Adult Males," Presented at Ninth Annual Air Pollution Medical Research Conference, Denver, Colorado (1968).

23. Toyama, T., "Studies on Aerosols. I. Synergistic Response of the Pulmonary Airway Resistance of Inhaling Sodium Chloride Aerosols and SO_2 in Man," Japan J. Ind. Health, 4, 86 (1962).

24. Nakamura, K., "Response of Pulmonary Airway Resistance by Interaction of Aerosols and Gases in Different Physical and Chemical States," *Japan J. Hyg.*, **19**, 322 (1964).

25. Toyama, T., and K. Nakamura, "Synergistic Response of Hydrogen Peroxide Aerosols and Sulfur Dioxide to Pulmonary Airway Resistance," *Ind. Health*, **2**, 34 (1964).

26. Speizer, F. E., "An Epidemiological Appraisal of the Effects of Ambient Air on Health: Particulates and Oxides of Sulfur," *JAPCA*, **19**, 647-656 (1969).

27. Winkelstein, W., "The Relationship of Air Pollution to Cancer of the Stomach," *Arch. Environ. Health*, **18**, 544-547 (1969).

28. Zeidburg, L. D., R. M. Hagstrom, H. A. Sprague and E. Landau, "Nashville Air Pollution Study. VII. Mortality from Cancer in Relation to Air Pollution," *Arch. Environ. Health*, **15**, 237-248 (1967).

29. Zeidberg, L. D., R. J. M. Horton and E. Landau, "The Nashville Air Pollution Study. V. Mortality from Diseases of the Respiratory System in Relation to Air Pollution," *Arch. Environ. Health*, **15**, 214-224 (1967).

30. Fletcher, C. M., B. M. Tinker, I. D. Hill and F. E. Speizer, "A Five-Year Prospective Field Study of Chronic Bronchitis," Preprint. (Presented at the 11th Aspen Conference on Research in Emphysema June 1968.)

31. Douglas, J. W. B., and R. E. Waller, "Air Pollution and Respiratory Infection in Children," *Brit. J. Prevent. Soc. Med.*, **20**, 1-8 (1966).

32. Lunn, J. E., J. Knowelden and A. J. Handyside, "Patterns of Respiratory Illness in Sheffield Infant School Children," *Brit. J. Prevent. Soc. Med.*, **21**, 7-16 (1967).

33. Watanabe, H., "Air Pollution and Its Health Effects in Osaka, Japan," Preprint. (Presented at the 58th Annual Meeting, Air Pollution Control Association, Toronto, Canada, June 20-24, 1965.)

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APPENDIX C

MODIFICATION OF THE ATMOSPHERE BY PARTICULATE POLLUTION

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Summary

Suspended fine particles may have considerable influence on the behavior of the atmosphere and thus on human activities. They can act as condensation or freezing nuclei and thereby modify weather patterns. They absorb and scatter light and decrease visibility. Fine particles in the atmosphere may also influence solar radiation and interfere with astronomical observations.

Visibility reduction related to air pollution is caused primarily by the 0.1 to 1.0 μ radius particles in the atmosphere. The visibility problem associated with particulate air pollution can be divided into specific smoke plumes and well-aged aerosols. The visual appearance of smoke plumes and visual obscuration by smoke plumes are closely related to the amount of light the plumes scatter in the direction of the viewer from their surroundings and the sun. Consequently, evaluation of plumes by a visual effect is more difficult for nonblack plumes than for black plumes, and depends on plume illuminating and viewing conditions. Because of this, nonblack plumes could be evaluated differently when viewed on different days or viewed from different directions, though their aerosol content has not changed. Furthermore, the size of particles and mass per unit time emitted from the stack, and not the appearance or optical properties of the plume, are more important to the eventual air composition, even though appearance may be aesthetically objectionable.

Recent advances in our knowledge of the size distributions and optical properties of well-aged atmospheric aerosols have resulted in a clearer description of visibility reduction by such aerosols. Theoretical and experimental studies of well-aged aerosols have shown that:

1. Aerosols in the lowest region of the atmosphere (troposphere), whether over urban areas or not, tend to have similar size distributions.

2. A narrow range of particle sizes, usually from 0.1 to 1.0 μ radius, controls the extinction coefficient and thereby visibility.

3. The mass concentration of a well-aged aerosol is approximately proportional to the light scattering coefficient for atmospheric aerosols originating naturally or as the result of man's activity.

The increased emission of fine particles into the atmosphere may cause changes in the delicate heat balance of the earth-atmosphere system, thus altering worldwide climatic conditions. Comparisons at different sites over the world covering periods of up to 50 years suggest that a general worldwide rise in turbidity may be taking place. This may well be indicative of a gradual buildup of worldwide background levels of suspended

particulates. The net influence of atmospheric turbidity on surface temperature is uncertain, but the emission of long-lived particles may well be leading to a decrease in world air temperature. As more is learned about the general circulation of the atmosphere and the delicate balance between incoming and outgoing radiation, it seems increasingly probable that small changes such as those occasioned by increasing particle loads in the atmosphere may produce very long-term meteorological effects.

Suspended particulate matter may alter weather patterns. There is evidence that some of the particles introduced into the atmosphere by man's activities can act as nuclei in processes which affect the formation of clouds and precipitation. Investigations of snow and rainstorm patterns indicate that submicroscopic particulates from man-made pollution may be initiating and controlling precipitation in a primary manner, rather than being involved in the secondary process wherein precipitation elements coming from natural mechanisms serve to remove the particles by diffusion, collision, and similar scavenging processes.

1. Introduction

The suspended atmospheric particles are of four general types. The first are the "light ions" produced in the air by cosmic rays and radioactivity. They consist of small aggregates of molecules having dimensions up to a few molecular diameters. The second important type of particle consists of the so-called "aitken nuclei." These particles range in radius from 2 x 10^{-7} cm. up to 10^{-4} cm. They are particularly prevalent near cities and the earth's surface. As a rule of thumb, one anticipates finding about 100,000 of these particles per cm^3 in a large city, about 10,000/cm^3 in the country, and about 1,000/cm^3 at sea. The numbers decrease with increasing altitude and only about 10% of the surface populations are found at an altitude of 7 km. The fine particle pollution of the air is largely composed of these nuclei.

The third type of atmospheric particle is the cloud droplet having a radius from 10^{-4} cm. to 5 x 10^{-3} cm. Finally, the cloud droplets associate to form raindrops or snowflakes that fall at velocities dependent upon their size. Rain or snow represents the final stage for the removal of atmospheric pollution by natural methods.

Suspended fine particles may have considerable influence on the behavior of the atmosphere and thus on human activities. They can act as condensation or freezing nuclei and thereby modify weather patterns. They absorb and scatter light and decrease visibility. Fine particles in the atmosphere may also influence solar radiation and interfere with astronomical observations. These facets of fine particulate pollution are reviewed in the following sections.

2. Visibility

Decreased visibility obviously interferes with certain human activities, such as safe operation of aircraft and automobiles and the enjoyment of scenic vistas. Air pollution that reduces visibility, in addition to endangering the safety of both air and land travel, results in inconvenience and economic loss to the public, and to transportation companies due to disruption of traffic schedules.

Visibility reduction related to air pollution is caused primarily by the 0.1 to 1.0 μ radius particles in the atmosphere. Deterioration of visibility caused by suspended particulate matter is the result of absorption and scattering of light. Both the brightness of the viewed object and its visual contrast with the background are reduced by attenuation of light due to scattering and absorption. In addition, a further contrast reduction results from scattering of sunlight into the observer's line of sight. Loss of brightness and contrast are responsible for the subjective impression of impaired visibility.

The visibility problem associated with particulate air pollution can be divided into specific smoke plumes and well-aged aerosols. The visual appearance of smoke plumes and visual obscuration by smoke plumes are closely related to the amount of light the plumes scatter in the direction of the viewer from their surroundings and the sun. Consequently, evaluation of plumes by a visual effect is more difficult for nonblack plumes than for black plumes, and depends on plume illuminating and viewing conditions. Because of this, nonblack plumes could be evaluated differently when viewed on different days or viewed from different directions, though their aerosol content has not changed.

At least two real difficulties exist in making any generalizations about visual aspects of smoke plumes. First, it is not possible to determine the mass emitted per unit time from a smokestack solely on the basis of visually perceived light scatter or absorption. The size and mass per unit time emitted from the stack, and not the appearance or optical properties of the plume, are pertinent to the eventual air composition, even though appearance may be aesthetically objectionable.

Second, although many meteorological mixing equations have been proposed, they cannot describe individual eddies of smoke as the plume disintegrates. The equations were meant for describing averages and not an instantaneous property such as the extinction of light on some particular eddy of smoke as determined by eye.

The problem of measuring the contribution of individual plumes to overall visibility reduction in a specific locality is extremely complex and more detailed study is necessary to develop improved techiques. Reference 1 presents a detailed study of plume optics, and the reader is referred to it for further information.

Recent advances in our knowledge of the size distributions and optical properties of well-aged atmospheric aerosols have resulted in a clearer description of visibility reduction by such aerosols. Theoretical and experimental studies of well-aged aerosols have shown that:

1. Aerosols in the lowest region of the atmosphere (troposphere), whether over urban areas or not, tend to have similar size distributions.[2-5]

2. A narrow range of particle sizes, usually from 0.1 to 1.0 μ radius, controls the extinction coefficient and thereby visibility.[6-8]

3. The mass concentration of well-aged aerosols is approximately proportional to the light scattering coefficient for atmospheric aerosols originating naturally or as the result of man's activity.[9]

Studies by Charlson, et al.,[9] and Noll, et al.,[10] suggest that a useful relationship between visual range and mass concentration of atmospheric particulate matter can be obtained from the observation that mass concentration is approximately proportional to the scattering coefficient. The visual range is defined as the distance, under daylight conditions, at which the apparent contrast between object and background is just equal to the threshold contrast of the observer. The usual assumption of threshold contrast of 0.02 for the human eye leads to the expression[1-3]

$$L = 3.9/b \qquad (1)$$

where L is the visual range in meters and b is the extinction coefficient per meter along the sight path for a black target.

Combining Eq. (1) with the observation that the mass concentration is approximately proportional to "b" results in Eq. (2)

$$L = kM^{-1} \qquad (2)$$

where M is the mass concentration of particulate matter.

From observations on the urban atmospheric aerosol in Berkeley, California, and using two different methods of measuring visual range (Volz photometer and Oakland Airport visibility) Noll, et al.,[10] found values of k in the range 1.6 to 1.9 g^{-2}. The average value of k for measurements made in New York City, San Jose, and Seattle reported by Charlson, et al.,[11] is 1.2 g^{-2}; this figure subsequently was corrected to a value of 1.8 g^{-2} on the basis of improved instrument calibration.[12] Fett[13] in Berlin found a modal value for k of about 1.8 g^{-2} from visual observations. The agreement between these measurements, in spite of the diversity of character of the pollution in the observing locations and different methods of measurement (nephelometer, sun photometer, and visual observations) implies approximate similarity of the particle-size distribution for the various observing locations.

More important for purposes of air pollution control, however, the apparent generality of the value of k for the urban aerosol (within the limitations of relative humidity below 70% and sufficient separation from sources to allow aerosol aging) suggests that these results will be useful in the estimation of the effects of control of emissions of particulate matter on visibility, provided the control techniques applied do not alter the size distribution of the aged aerosol.

Photochemically produced aerosols, as well as other organic aerosols, can be expected to have similar visibility effects if their size distribution remains reasonably constant. Since the physical processes governing size distribution are assumed to be largely independent of the chemical nature of the particles,[3] the size distribution should be similar to those found for other atmospheric aerosols.

The optical properties of aerosols are a very active research area and new data are constantly being acquired. Improvements in the understanding of these phenomena and the accuracy of descriptions will no doubt occur in the near future.

3. Solar Radiation and Weather Modification

3.1 Discussion

Particles in the atmosphere play several roles in the behavior and determination of the weather. Among the most obvious is the effect they have on the radiation from the sun. They scatter the light to greater or lesser extents in different wavelength regions, depending on their size, character, and concentration, and thus provide the sky with its variable hues, its colorful dawns and sunsets, and also dense hazes and dark urban palls.

The increased emission of fine particles into the atmosphere also may cause changes in the delicate heat balance of the earth-atmosphere system, thus altering worldwide climatic conditions. The rise in atmospheric turbidity increases the planetary reflectivity, and may reduce the solar energy available to maintain surface temperatures.

Suspended particulate matter may alter weather patterns. Particles are essential to cloud formation; without particles liquid water clouds could not form except when the air was supersaturated. Nature supplies in overabundance the particles required for cloud formation. The kinds of particles which cause precipitation from clouds, in contrast to those necessary for cloud formation, are frequently in short supply in the atmosphere. In warm (above freezing) clouds, the requirement is a wide distribution of condensation nuclei, some greater than 1 μ. Another kind is required to stimulate the rapid transformation of cloud droplets into precipitation in supercooled (subfreezing) parts of clouds. Such particles are termed freezing nuclei. Without these, the water droplets would not freeze except at temperatures below -40°C. There is evidence that some of the particles introduced into the atmosphere by man's activities can act as nuclei in processes which affect the formation of clouds and precipitation.

The potential influence of fine particles on solar radiation and weather patterns is discussed separately in the next two sections.

3.2 Solar Radiation

The intensity and spectral distribution of direct sunlight and scattered daylight, and the variation of intensity with time of day, season, latitude, altitude, and atmospheric conditions are important because they affect photosynthesis in plants and the distribution of plants and animals on earth, the weathering of natural and man-made materials, climate, and illumination for human activity.[15]

The attenuation of solar radiation through the atmosphere is caused by a number of physical factors:[14-16]

1. Rayleigh scattering by air molecules such as N_2 and O_2, and particles in size ranges less than the wavelength of solar radiation;

2. Selective absorption by gaseous constituents of the atmosphere; and

3. Scattering and absorption by atmospheric dusts and particulate matter of a size greater than the wavelength of solar radiation.

The scattering of light by aerosol particles in ambient air is a complicated process. Part of the light is transmitted, part is reflected in all directions either at the front surface of the particle or at an internal discontinuity and part is absorbed. The transmission factor for scattering is a function of the wavelength of the incident light and the physical qualities of the scattering medium. In simple cases where the form, size, and composition of scattering particles are known, the factor can be derived on a theoretical basis and is known as "Mie" scattering.

Except in cases of heavy particulate pollution of the atmosphere, such as may occur in large urban centers or heavy industrial areas, it appears that the effect of turbidity is to scatter radiation out of the direct solar beam and add an almost equal amount to the diffuse beam arriving from the rest of the sky by forward-scattering. In cases of heavy particle concentrations, however, the loss from the direct solar beam greatly exceeds the gain in the downward scattered beam, the difference being lost to backscattering off the top of the pollution layer, and to absorption within the polluted layer or column.

Landsberg[17] and Steinhauser[18] report that cities in general receive less solar radiation than do their rural environments. Seasonal, weekly, and daily variations in total solar radiation in urban comunities have also been noted.[18-20] These variations appear to be related, in part, to cycles of industrial and commercial activity.

Comparisons at different sites over the world covering periods of up to 50 years suggest that a general worldwide rise in turbidity may be taking place. This may well be indicative of a gradual buildup of worldwide background levels of suspended particulates.[27] The net influence of atmospheric turbidity on surface temperature is uncertain, but the emission of long-lived particles may well be leading to a decrease in world air temperature.[21] As more is learned about the general circulation of the atmosphere and the delicate balance between incoming and outgoing radiation, it seems increasingly probable that small changes such as those occasioned by increasing particle loads in the atmosphere may produce very long-term meteorological effects.

3.3 Weather Modification

As noted previously, there is evidence that some of the particles introduced into the atmosphere by man's activity can act as nuclei in processes which affect the formation of clouds and precipitations. An example of increased precipitation from air pollution appears to exist at La Porte, Indiana, some 30 miles downwind from the heavy industrial complex in Chicago. Precipitation and thunderstorm activity have increased significantly since 1925, and precipitation peaks have coincided with peaks in steel production in the Chicago area.[22] Hobbs, _et al_.[23] have reported measurements of the concentrations of cloud condensation nuclei in Washington State resulting from pulp and paper mills and other industrial sources. Their study of the precipitation and stream flow records in Washington State for the past 40 years revealed that in recent years there have been significant increases in precipitation in several areas in the vicinity of large industrial sources of cloud-condensation nuclei.

Excessive dustiness in the atmosphere can also reduce rainfall under certain conditions when overseeding occurs. This happens when many small droplets, formed by condensation, do not fall to earth if there is insufficient moisture available to continue the droplet growth by condensation. Consequently, what would have fallen as rainfall stays in the form of clouds. A case in point of this reduction in rainfall has occurred in the sugar producing area in Queensland, Australia. During the cane harvesting season, the common practice is to burn off the cane leaf before cutting and harvesting. This results in fires over extensive areas and large palls of smoke. The fine smoke particles have modified the cloud formation and hindered the rainfall process. A reduction of up to 25% in the rainfall has occurred downwind of these areas, but there is no such effect in neighboring areas unaffected by the smoke plume.[24] Similar effects have been reported in Puerto Rico, Africa, and Hawaii.[25,26] Schaefer has also reported on observations of changes in micro-physics of clouds in the vicinity of large cities during airplane flights through convective clouds.[25] His observations suggest that such clouds contain an increasing number of cloud droplets. Schaefer's investigations of snow and rainstorm patterns in New York State indicate that submicroscopic particulates from man-made pollution may be initiating and controlling precipitation in a primary manner, rather than being involved in the secondary process wherein precipitation elements coming from natural mechanisms serve to remove the particles by diffusion, collision, and similar scavenging processes.

REFERENCES

1. Connor, W. D., and J. R. Hodkinson, *Optical Properties and Visual Effects of Smoke-Stack Plumes*, PHS Publ. No. 999-AP-30, Cincinnati, Ohio (1967).

2. Junge, C. E., *Air Chemistry and Radioactivity*, Academic Press, New York (1963).

3. Friedlander, S. K., and C. S. Wang, "The Self-Preserving Particle Size Distribution for Coagulation by Brownian Motion," *J. Colloid Interface Sci.*, **22**, 126-132 (1966).

4. Whitby, K. T., and W. E. Clark, "Electric Aerosol Particle Counting and Size Distribution Measuring System for the 0.15 μ to 1 μ Size Range," *Tellus*, **18**, 573-586 (1966).

5. Peterson, C. M., and H. J. Paulus, "Micrometeorological Variables Applied to the Analysis of Variation in Aerosol Concentration and Size," Preprint. (Presented at the 60th Annual Meeting, Air Pollution Control Association, Cleveland, Ohio, June 11-16, 1967).

6. Mie, G., "Beitrage zur Optik truber Medien, Speziell Kolloidaler Metallosungen," *Ann. Physik*, **25**, 377-455 (1968).

7. Pueschel, R. F., and K. E. Noll, "Visibility and Aerosol Size Frequency Distribution," *J. Appl. Meteorol.*, **6**, 1045-1052 (1967).

8. *Air Quality Criteria for Particulate Matter*, NAPCA Publ. AP-49, Washington, D. C. (1969).

9. Charlson, R. J., H. Horvath, and R. F. Pueschel, "The Direct Measurement of Atmospheric Light Scattering Coefficient for Studies of Visibility and Air Pollution," *Atmos. Environ.*, **1**, 469-478 (1967).

10. Noll, K. E., P. K. Mueller, and M. Imada, *Atmos. Environ.*, **1**, 501 (1967).

11. Charlson, R. J., N. Ahlquist, and H. Horvath, *Atmos. Environ.*, **2**, 300 (1968).

12. Charlson, R. J., N. Ahlquist, and H. Selvidge, "The Use of the Integrating Nephelometer for Monitoring Particulate Pollution," Presented at 10th Conference on Methods, San Francisco (1969).

13. Fett, W., *Beitr. Phys. Atmos.*, **40**, 262 (1967).

14. McCormick, R. A., and D. M. Baulch, "The Variation with Height of the Dust Loading Over a City as Determined from the Atmospheric Turbidity," *JAPCA*, **12**, 492-496 (1962).

15. Gates, D. M., "Spectral Distribution of Solar Radiation at the Earth's Surface," *Science*, **151**, 523-529 (1966).

16. Robinson, N., *Solar Radiation*, Elsevier, Amsterdam, London, and New York (1966).

17. Landsberg, H., *Physical Climatology*, 2nd Edition, Gray, Dubois, Pennsylvania, 317-326 (1958).

18. Steinhauser, F., O. Eckel, and F. Sauberer, "Klima und Bioklima von Wien," *Wetter und Leben*, **7** (1955).

19. Meetham, A. R., *Atmospheric Pollution: Its Origins and Prevention*, Pergamon Press, New York (1961).

20. Mateer, C. L., "Note on the Effect of the Weekly Cycle of Air Pollution on Solar Radiation at Toronto," *Intern. J. Air Water Pollution*, **4**, 52-54 (1961).

21. "Restoring the Quality of Our Environment," Report of the Environmental Pollution Panel, President's Science Advisory Committee. The White House, Washington, D. C., 111-131, November 1965.

22. Changnon, S. A., "The LaPorte Weather Anomaly--Fact or Fiction," *Bulletin of American Meteorological Society*, **49** (1), 4-11 (1968).

23. Hobbs, P. V., *et al.*, "Cloud Condensation Nuclei from Industrial Sources and Their Apparent Influence on Precipitation in Washington State," *Journal of Atmospheric Sciences*, **27**, 81-89 (1970).

24. Aynsley, E., "How Air Pollution Alters Weather," *New Scientist*, 66-67, October 9, 1969.

25. Schaefer, V. J., "The Inadvertent Modification of the Atmosphere by Air Pollution," *Bulletin of American Meteorological Society*, **50** (4), 199-206 (1969).

26. Warner, J., "A Reduction in Rainfall Associated with Smoke from Sugar Cane Fires - An Inadvertent Weather Modification," *J. Applied Meteorology*, **7**, 247-251 (1968).

27. Gunn, R., "The Secular Increase of the World-Wide Fine Particle Pollution," *J. Atmos. Sci.*, **21**, 168-181 (1964).

APPENDIX D

DATA SOURCES

I. Companies that provided data

Organization	Sources
1. TVA	10 distributions - power plants (before and after control devices)
2. Coulter Electronics	4 distributions - power plants and cement plants (before control)
3. Koppers Company	6 distributions - power plants (before control)
4. H. W. Dieteret Company (Bahco sales representative)	6 miscellaneous distributions by Bahco methods
5. PEDCo - Environmental	2 distributions - power plants (before control)
6. Resources Research	Compilation of 25-30 particle size distributions for several sources--power plants, kilns, dryers, electric furnaces
7. Roy F. Weston Company	6 distributions - power plants (before control)
8. Abe Matthews Engineering Company	15 distributions - cupolas, power plant, lime kiln, cement kiln, mineral processing (before control)
9. George Clayton Associates	10 distributions - power plant, cupolas, lime kiln, cement kiln, electric furnace (before control)
10. Universal Oil Products (Air Correction Division)	25 distributions - power plant (before and after control)
11. Western Precipitator	Compilation of 250-300 particle size distributions--12-15 different sources (before control)
12. National Dust Collector	9 distributions - cupola, coal cleaning, asphalt dryers, and mineral processing (electron microscope data, before and after control)

	Organization	Sources
13.	Environmental Research Corporation	1 distribution - secondary aluminum
14.	Meteorology Research, Inc.	Power plant plume data

II. Other companies contacted that have data which were not acquired

1.	Cottrell Environmental	Data available, cost prohibitive
2.	American Air Filter	Data available, will work only through IGCI
3.	American Standard	Data not available for public disclosure
4.	Wheelabrator	Data not available for public disclosure
5.	Pulverizing Machinery	Data not available for public disclosure
6.	Buffalo Forge	Data not available for public disclosure

III. Research groups

1.	Dr. M. Pilat University of Washington	Power plant, recovery furnace (pulp mill), plywood veneer dryer (cascade impactor)
2.	Prof. A. F. Bush UCLA	Power plant (thermal precipitator, electron microscope data)
3.	Dr. S. K. Friedlander Cal Tech	No source data
4.	Dr. P. K. Mueller California Department of Public Health	No source data
5.	Dr. A. Cohen Ecological Research Branch APCO, Durham	No source data

6.	Dr. Jack Wagman Division of Chemical and Physical Research and Development APCO, Durham	No source data
7.	Dr. Myron Robinson Atomic Energy Commission	No source data
8.	Prof. M. Kerker Clarkson College	No source data
9.	Dr. Mary Amdur Harvard School of Public Health	No source data

IV. Companies contacted that did not have data

1. Mr. J. Katz
Jacob Katz Associates

2. Mr. Jorgen Hedenhag
Polycom Corporation

3. Mr. Charles Billings
GCA

4. Mr. Ray Droger
Seversky Electronatom

5. Mr. Sid Orem
Flyash Arrestor

6. Mr. I. Shah
Chemico

7. Mr. Ballard
Menardi and Company

8. Mr. Charles Cook
Mine Safety Appliances Company

9. Mr. Dick Glover
Monsanto Environmental Control System

10. Mr. J. Pizzo
U. S. Testing Company, Inc.

11. Mr. R. E. Sommerclad
Foster Wheeler Corporation

12. Mr. A. Lieberman
Royco Instruments

13. Dr. William A. Perkins
Metronics Associates

14. Mr. H. D. Wheeler
Kaiser Engineers

15. Dr. M. Feldstein
Bay Area Air Pollution Control District

16. Mr. Walter Hamming
Los Angeles APCD

17. Dr. E. R. Hendrickson
Environmental Engineering, Inc.

APPENDIX E

CALCULATIONS OF FINE-PARTICLE EMISSIONS

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TABLE E-1

SUMMARY OF FINE-PARTICLE EMISSIONS FROM ASPHALT DRYERS
(Tons/Year)

Source - Asphalt

Process - Dryers

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Cy + Wet	FF	
1-3	5,100		18,300	73,000		96,400
0.5-1.0	900		3,900	31,500		36,300
0.1-0.5	300		1,400	19,800		21,500
0.05-0.1						
0.01-0.05						
	6,300		23,600	124,300		154,200

TABLE E-2

DISTRIBUTION OF PROCESS EMISSIONS FROM ASPHALT DRYERS

Source - Asphalt

Process - Dryers

Production (tons/year) Emission Factor (lb/ton)

Process Emissions = (251×10^6) (32) $\left(\frac{1}{2{,}000}\right)$ = 4,016,000 tons/year

Application of Control = 99 %

Process Emissions into Uncontrolled Plants = 40,200 tons/year

Process Emissions into Controlled Plants = 3,975,800 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
Cyclone	5	198,800
Cyclone + Scrubber	95	3,777,000
FF	?	

TABLE E-3

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED ASPHALT DRYERS

Process - Asphalt Dryers

Control Device - Uncontrolled

Process Emissions into Control Device 40,200 tons/year

Process Emissions		Control Device Uncontrolled	Control Device	
Size (μ)	Percent	Penetration (%) (1 - efficiency)	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	12.6	100		5,100
0.5-1.0	2.18	100		900
0.1-0.5	0.71	100		300
0.05-0.1				
0.01-0.05				
				6,300

TABLE E-4

FINE-PARTICLE EMISSIONS FROM ASPHALT DRYERS CONTROLLED BY CYCLONES

Process - Asphalt Dryers

Control Device - Cyclones

Process Emissions into Control Device 198,800 tons/year

Process Emissions		Control Device	Control Device	
		Cyclones		
Size (μ)	Percent	Penetration (%) (1 - efficiency)[a]	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	12.6	73		18,300
0.5-1.0	2.18	89		3,900
0.1-0.5	0.71	100		1,400
0.05-0.1				
0.01-0.05				
				23,600

---

[a] Efficiency values were taken from medium fractional efficiency curve, Figure 17.

TABLE E-5

FINE-PARTICLE EMISSIONS FROM ASPHALT DRYERS CONTROLLED BY CYCLONES PLUS SCRUBBER

Process - Asphalt Dryers

Control Device - Cyclones plus Scrubber

Process Emissions into Control Device 3,777,000 tons/year

Process Emissions Size (μ)	Process Emissions Percent	Control Device Cyclone Penetration (%) (1 - efficiency)[a]	Control Device Scrubber Penetration (%) (1 - efficiency)[a]	Emissions (tons/year)
1-3	12.6	73	21	73,000
0.5-1.0	2.18	89	43	31,500
0.1-0.5	0.71	100	74	19,800
0.05-0.1			95	
0.01-0.05			100	
				124,300

---

[a] Efficiency values were taken from medium fractional efficiency curve, Figure 17.

TABLE E-6

SUMMARY OF FINE-PARTICLE EMISSIONS FROM VENT LINES

(Tons/Year)

Source - Asphalt

Process - Vent Line

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Cy + Wet	FF	
1-3	800		2,700	10,900		14,400
0.5-1.0			200	1,500		1,700
0.1-0.5				200		200
0.05-0.1						
0.01-0.05						
	800		2,900	12,600		16,300

TABLE E-7

DISTRIBUTION OF PROCESS EMISSIONS FROM VENT LINES

Source - Asphalt

Process - Vent Line

Process Emissions = $\underset{\text{Production (tons/year)}}{(251 \times 10^6)} \; \underset{\text{Emission Factor (lb/ton)}}{(8)} \left(\frac{1}{2,000}\right)$ = 1,004,000 tons/year

Application of Control = 99 %

Process Emissions into Uncontrolled Plants = 10,000 tons/year

Process Emissions into Controlled Plants = 994,000 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
Cyclone	5	49,700
Cyclone plus Scrubber	95	944,300

TABLE E-8

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED VENT LINES

Process - Asphalt - Vent Lines

Control Device - Uncontrolled

Process Emissions into Control Device 10,000 tons/year

Process Emissions Size (μ)	Percent	Control Device Uncontrolled Penetration (%) (1 - efficiency)	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	7.55	100		800
0.5-1.0	0.41	100		
0.1-0.5	0.03	100		
0.05-0.1				
0.01-0.05				
				800

TABLE E-9

FINE-PARTICLE EMISSIONS FROM VENT LINES CONTROLLED BY CYCLONES

Process - Asphalt - Vent Lines

Control Device - Cyclone

Process Emissions into Control Device 49,700 tons/year

Process Emissions		Control Device	Control Device	
		Cyclone		
Size (μ)	Percent	Penetration (%) (1 - efficiency)[a]	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	7.55	73		2,700
0.5-1.0	0.41	89		200
0.1-0.5	0.03	100		
0.05-0.1				
0.01-0.05				
				2,900

---

[a] Efficiency values were taken from medium fractional efficiency curve, Figure 17.

TABLE E-10

FINE-PARTICLE EMISSIONS FROM VENT LINES CONTROLLED BY CYCLONES PLUS SCRUBBER

Process - Asphalt - Vent Lines

Control Device - Cyclone plus Scrubber

Process Emissions into Control Device 944,300 tons/year

Process Emissions Size (μ)	Process Emissions Percent	Control Device Cyclone Penetration (%) (1 - efficiency)[a]	Control Device Scrubber Penetration (%) (1 - efficiency)[a]	Emissions (tons/year)
1-3	7.55	73	21	10,900
0.5-1.0	0.41	89	43	1,500
0.1-0.5	0.03	100	74	200
0.05-0.1			95	
0.01-0.05			100	
				12,600

---

[a] Efficiency values were taken from medium fractional efficiency curve, Figure 17.

TABLE E-11

SUMMARY OF FINE-PARTICLE EMISSIONS FROM CEMENT KILNS
(Tons/Year)

Source - Cement Plants

Process - Kilns

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Cy + ESP	FF	
1-3	36,300	29,400	58,300	6,400	400	130,800
0.5-1.0	6,500	8,200	15,100	2,600	300	32,700
0.1-0.5	2,000	4,300	5,400	1,600	200	13,500
0.05-0.1						
0.01-0.05						
	44,800	41,900	78,800	10,600	900	177,000

TABLE E-12

DISTRIBUTION OF PROCESS EMISSIONS FROM CEMENT KILNS

Source - Cement Plants

Process - Kilns

$$\text{Process Emissions} = \overset{\text{Production (tons/year)}}{(74.6 \times 10^6)} \quad \overset{\text{Emission Factor (lb/ton)}}{(167)} \left(\frac{1}{2,000}\right) = 6.299 \times 10^6 \text{ tons/year}$$

Application of Control = 94 %

Process Emissions into Uncontrolled Plants = 0.374×10^6 tons/year

Process Emissions into Controlled Plants = 5.855×10^6 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
ESP	47	2.752×10^6
Cyclones	18	1.054×10^6
Cy + ESP	18	1.054×10^6
FF	17	0.995×10^6

TABLE E-13

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED CEMENT KILNS

Process - Cement Kilns

Control Device - Uncontrolled

Process Emissions into Control Device 0.374 x 10^6 tons/year

Process Emissions Size (µ)	Process Emissions Percent	Control Device Uncontrolled Penetration (%) (1 - efficiency)	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	9.7	100		36,300
0.5-1.0	1.75	100		6,500
0.1-0.5	0.54	100		2,000
0.05-0.1				
0.01-0.05				
				44,800

TABLE E-14

FINE-PARTICLE EMISSIONS FROM CEMENT KILNS CONTROLLED BY ELECTROSTATIC PRECIPITATORS

Process - Cement Kilns

Control Device - Electrostatic Precipitators

Process Emissions into Control Device 2.752×10^6 tons/year

Process Emissions		Control Device ESP	Control Device X	
Size (μ)	Percent	Penetration (%) (1 - efficiency)[a]	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	9.7	11		29,400
0.5-1.0	1.75	17		8,200
0.1-0.5	0.54	29		4,300
0.05-0.1				
0.01-0.05				
				41,900

---

[a] Efficiency values used were taken from average fractional efficiency curve, Figure 17.

Note: Outlet particle size distribution for cement kiln controlled by ESP showed 43% $< 3\ \mu$. (Figure 34).

If the overall efficiency of ESP's is assumed to average about 95%, then the quantity emitted by ESP controlled plants is as follows:

$(2.752 \times 10^6$ tons/year$)(1-0.95)(43\%) = 59{,}200$ tons/year $< 3\ \mu$.

The 59,200 tons/year gives a cross-comparison with 41,900 tons/year.

TABLE E-15

FINE-PARTICLE EMISSIONS FROM CEMENT KILNS CONTROLLED BY CYCLONES

Process - Cement Kilns

Control Device - Cyclones

Process Emissions into Control Device 1.054 x 10^6 tons/year

Process Emissions Size (μ)	Process Emissions Percent	Control Device Cyclones Penetration (%) (1 - efficiency)[a]	Control Device X Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	9.7	57		58,300
0.5-1.0	1.75	82		15,100
0.1-0.5	0.54	94		5,400
0.05-0.1				
0.01-0.05				
				78,800

---

[a] Efficiency values used were taken from fractional efficiency curve for high efficiency cyclones, Figure 17, because some plants use multiclones and since the dust is reusable to a certain extent, it is assumed that higher efficiency devices would be used.

TABLE E-16

FINE-PARTICLE EMISSIONS FROM CEMENT KILNS CONTROLLED BY CYCLONES PLUS ELECTROSTATIC PRECIPITATOR

Process - Cement Kilns

Control Device - Cyclone + ESP

Process Emissions into Control Device 1.054 x 10^6 tons/year

Process Emissions Size (μ)	Process Emissions Percent	Control Device Cyclone Penetration (%) (1 - efficiency)	Control Device ESP Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	9.7	57	11	6,400
0.5-1.0	1.75	82	17	2,600
0.1-0.5	0.54	94	29	1,600
0.05-0.1				
0.01-0.05				
				10,600

TABLE E-17

FINE-PARTICLE EMISSIONS FROM CEMENT KILNS CONTROLLED BY FABRIC FILTERS

Process - Cement Kilns

Control Device - Fabric Filters

Process Emissions into Control Device 0.995 x 10^6 tons/year

Process Emissions		Control Device FF	Control Device X	
Size (μ)	Percent	Penetration (%) (1 - efficiency)	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	9.7	0.5		400
0.5-1.0	1.75	1.8		300
0.1-0.5	0.54	3.3		200
0.05-0.1				
0.01-0.05				
				900

TABLE E-18

SUMMARY OF FINE-PARTICLE EMISSIONS FOR FERROALLOY ELECTRIC FURNACES
(Tons/Year)

Source - Ferroalloys

Process - Electric Furnace

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Wet	FF	
1-3	18,300			100		18,400
0.5-1.0	27,500			300		27,800
0.1-0.5	79,400			1,700		81,100
0.05-0.1	16,800			500		17,300
0.01-0.05	7,500			200		7,700
	149,500			2,800		152,300

TABLE E-19

DISTRIBUTION OF PROCESS EMISSIONS FROM FERROALLOY ELECTRIC FURNACES
(Tons/Year)

Source - Ferroalloys

Process - Electric Furnaces

$$\text{Process Emissions} = \underset{\text{(tons/year)}}{\overset{\text{Production}}{(2.119 \times 10^6)}} \; \underset{\text{(lb/ton)}}{\overset{\text{Emission Factor}}{(240)}} \left(\frac{1}{2{,}000}\right) = 254{,}300 \text{ tons/year}$$

Application of Control = 40 %[a]

Process Emissions into Uncontrolled Plants = 152,600 tons/year

Process Emissions into Controlled Plants = 101,700 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
FF[b]	100[b]	101,700

---

a/ Page 233, Reference 1, showed 50% application of control. However, the 80% efficiency was mainly a result of capture efficiency. Control devices are high efficiency type, such as baghouses, Venturi scrubbers or disintegrators. Most are disintegrators and baghouses.

b/ Assume disintegrators are equivalent to fabric filters.

TABLE E-20

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED FERROALLOY ELECTRIC FURNACES

Process - Ferroalloys - Electric Furnace

Control Device - Uncontrolled

Process Emissions into Control Device 152,600 tons/year

Process Emissions		Control Device Uncontrolled	Control Device	
Size (μ)	Percent	Penetration (%) (1 - efficiency)	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	12	100		18,300
0.5-1.0	18	100		27,500
0.1-0.5	52	100		79,400
0.05-0.1	11	100		16,800
0.01-0.05	4.9	100		7,500
				149,500

TABLE E-21

FINE-PARTICLE EMISSIONS FROM FERROALLOY ELECTRIC FURNACES CONTROLLED BY FABRIC FILTERS AND DISINTEGRATORS

Process - Ferroalloys - Electric Furnace

Control Device - Fabric Filters and Disintegrators[a]

Process Emissions into Control Device 101,700 tons/year

Process Emissions		Control Device FF + Disinter	Control Device	
Size (μ)	Percent	Penetration (%) (1 - efficiency)[a]	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	12	0.5		100
0.5-1.0	18	1.8		300
0.1-0.5	52	3.3		1,[illegible]00
0.05-0.1	11	4.2		500
0.01-0.05	4.9	4.5		200
				2,800

---

[a] Assume disintegrators are equivalent to fabric filters.

TABLE E-22

SUMMARY OF FINE-PARTICLE EMISSIONS FROM FERTILIZER GRANULATORS AND DRYERS
(Tons/Year)

Source - Fertilizer

Process - Granulation and Drying

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Wet	FF	
1-3	1,400			5,700		7,100
0.5-1.0	400			3,100		3,500
0.1-0.5	200			2,900		3,100
0.05-0.1						
0.01-0.05						
	2,000			11,700		13,700

TABLE E-23

DISTRIBUTION OF PROCESS EMISSIONS FROM GRANULATOR AND DRYER

Source - Fertilizer

Process - Granulation and Drying

Process Emissions = Production (tons/year) (18.1×10^6) Emission Factor (lb/ton) (195) $\left(\frac{1}{2,000}\right)$ = 1,764,800 tons/year

Application of Control = 95 %

Process Emissions into Uncontrolled Plants = 88,200 tons/year

Process Emissions into Controlled Plants = 1,676,600 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
Wet Scrubbers	100	1,676,600

TABLE E-24

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED GRANULATORS AND DRYERS

Process - Fertilizer, Granulation and Drying, etc.

Control Device - Uncontrolled

Process Emissions into Control Device 88,200 tons/year

Process Emissions		Control Device Uncontrolled	Control Device	
Size (µ)	Percent	Penetration (%) (1 - efficiency)	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	1.62	100		1,400
0.5-1.0	0.43	100		400
0.1-0.5	0.23	100		200
0.05-0.1				
0.01-0.05				
				2,000

TABLE [illegible]-25

FINE-PARTICLE EMISSIONS FROM GRANULATORS AND DRYERS CONTROLLED BY WET SCRUBBERS

Process - Fertilizer, Granulation and Drying, etc.

Control Device - Wet Scrubbers

Process Emissions into Control Device 1,676,600 tons/year

Process Emissions		Control Device Scrubber	Control Device	
Size (μ)	Percent	Penetration (%) (1 - efficiency)[a]	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	1.62	21		5,700
0.5-1.0	0.43	43		3,100
0.1-0.5	0.23	74		2,900
0.05-0.1		95		
0.01-0.05		100		
				11,700

---

[a] Efficiency values were taken from medium fractional efficiency curve, Figure 17.

TABLE E-26

SUMMARY OF FINE-PARTICLE EMISSIONS FROM BASIC OXYGEN FURNACES, IRON AND STEEL

(Tons/Year)

Source - Iron and Steel

Process - Basic Oxygen Furnace

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Venturi	FF	
1-3		400		500		900
0.5-1.0		3,300		15,600		18,900
0.1-0.5		8,900		144,800		153,700
0.05-0.1				1,000		1,000
0.01-0.05						
		12,600		161,900		174,500

TABLE E-27

DISTRIBUTION OF PROCESS EMISSIONS FROM BASIC OXYGEN FURNACE

Source - Iron and Steel

Process - BOF

Process Emissions = (48×10^6) Production (tons/year) (40) Emission Factor (lb/ton) $\left(\frac{1}{2,000}\right)$ = 960,000 tons/year

Application of Control = 100 %

Process Emissions into Uncontrolled Plants = 0 tons/year

Process Emissions into Controlled Plants = 960,000 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
ESP	42	403,200
Venturi	58	556,800

TABLE E-28

FINE-PARTICLE EMISSIONS FROM BASIC OXYGEN FURNACES CONTROLLED BY ELECTROSTATIC PRECIPITATOR

Process - Basic Oxygen Furnace

Control Device - Electrostatic Precipitator

Process Emissions into Control Device 403,200 tons/year

Process Emissions Size (μ)	Percent	Control Device ESP Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	6	1.6		400
0.5-1.0	36	2.3		3,300
0.1-0.5	57.8	3.8		8,900
0.05-0.1	0.2	5.5		
0.01-0.05		8.2		
				12,600

---

[a] Efficiency values were taken from high fractional efficiency curve, Figure 17.

TABLE E-29

FINE-PARTICLE EMISSIONS FROM BASIC OXYGEN FURNACES CONTROLLED BY VENTURI SCRUBBER

Process - Basic Oxygen Furnace

Control Device - Venturi Scrubber

Process Emissions into Control Device 556,800 tons/year

Process Emissions		Control Device Venturi	Control Device	
Size (μ)	Percent	Penetration (%) (1 - efficiency)	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	6	1.4		500
0.5-1.0	36	7.8		15,600
0.1-0.5	57.8	45		144,800
0.05-0.1	0.2	86		1,000
0.01-0.05				
				161,900

TABLE E-30

SUMMARY OF FINE-PARTICLE EMISSIONS FROM ELECTRIC ARC FURNACE, IRON AND STEEL

(Tons/Year)

Source - Iron and Steel

Process - Electric Arc Furnace

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Wet	FF	
1-3	3,600			100	100	3,800
0.5-1.0	2,200			200	100	2,500
0.1-0.5	3,800			1,000	400	5,200
0.05-0.1	900			300	100	1,300
0.01-0.05	1,000			400	100	1,500
	11,500			2,000	800	14,300

TABLE E-31

DISTRIBUTION OF PROCESS EMISSIONS FROM ELECTRIC ARC FURNACE

Source - Iron and Steel

Process - Electric Arc Furnace

$$\text{Process Emissions} = \underset{\text{Production (tons/year)}}{(16.8 \times 10^6)} \; \underset{\text{Emission Factor (lb/ton)}}{(10)} \left(\frac{1}{2{,}000}\right) = 84{,}000 \text{ tons/year}$$

Application of Control = 79 %

Process Emissions into Uncontrolled Plants = 18,000 tons/year

Process Emissions into Controlled Plants = 66,000 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
Wet Scrubber	11	7,300
ESP	7	4,600
FF	82	54,100

TABLE E-32

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED ELECTRIC AIR FURNACES

Process - Electric Arc Furnace

Control Device - Uncontrolled

Process Emissions into Control Device 18,000 tons/year

Process Emissions		Control Device Uncontrolled	Control Device	
Size (μ)	Percent	Penetration (%) (1 - efficiency)	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	20	100		3,600
0.5-1.0	12	100		2,200
0.1-0.5	21	100		3,800
0.05-0.1	5	100		900
0.01-0.05	5.6	100		1,000
				11,500

TABLE E-33

FINE-PARTICLE EMISSIONS FROM ELECTRIC ARC FURNACES CONTROLLED BY WET SCRUBBER

Process - Electric Arc Furnace

Control Device - Wet Scrubber

Process Emissions into Control Device 7,300 tons/year

Process Size (μ)	Emissions Percent	Control Device Wet Scrubber Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	20	9		100
0.5-1.0	12	26		200
0.1-0.5	21	62		1,000
0.05-0.1	5	92		300
0.01-0.05	5.6	98		400
				2,000

---

[a] Efficiency values were taken from high fractional efficiency curve, Figure 17.

TABLE E-34

FINE-PARTICLE EMISSIONS FROM ELECTRIC ARC FURNACES CONTROLLED BY ELECTROSTATIC PRECIPITATOR

Process - Electric Arc Furnace

Control Device - Electrostatic Precipitator

Process Emissions into Control Device 4,600 tons/year

Process Emissions		Control Device ESP	Control Device	
Size (μ)	Percent	Penetration (%) (1 - efficiency)[a]	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	20	1.6		
0.5-1.0	12	2.3		
0.1-0.5	21	3.8		
0.05-0.1	5	5.5		
0.01-0.05	5.6	8.2		
				≈ 100

---

[a] Efficiency values were taken from high fractional efficiency curve, Figure 17.

TABLE E-35

FINE-PARTICLE EMISSIONS FROM ELECTRIC ARC FURNACES CONTROLLED BY FABRIC FILTER

Process - Electric Arc Furnace

Control Device - Fabric Filter

Process Emissions into Control Device 54,100 tons/year

Process Emissions		Control Device FF	Control Device	
Size (μ)	Percent	Penetration (%) (1 - efficiency)	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	20	0.5		100
0.5-1.0	12	1.8		100
0.1-0.5	21	3.3		400
0.05-0.1	5	4.2		100
0.01-0.05	5.6	4.5		100
				800

TABLE E-36

SUMMARY OF FINE-PARTICLE EMISSIONS FROM OPEN HEARTH FURNACES

(Tons/Year)

Source - Iron and Steel

Process - Open Hearth

1. Based on Particle Size Distribution in Lower Right of Figure 26.

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Cy + ESP	FF	
1-3	56,200	4,300				60,500
0.5-1.0	49,600	5,900				55,500
0.1-0.5	194,900	39,300				234,200
0.05-0.1	17,200	4,900				22,100
0.01-0.05	2,600	1,000				3,600
	320,500	55,400				375,900

2. Based on "Composite" Particle Size Distribution in Figure 26.

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Cy + ESP	FF	
1-3	74,300	5,700				80,000
0.5-1.0	17,500	2,100				19,600
0.1-0.5	7,100	1,400				8,500
0.05-0.1	100					100
0.01-0.05						
	99,000	9,200				108,200

TABLE E-37

DISTRIBUTION OF PROCESS EMISSIONS FROM OPEN HEARTH FURNACES

Source - Iron and Steel

Process - Open Hearth

Process Emissions = Production (tons/year) (65.8 x 10^6) Emission Factor (lb/ton) (17) $\left(\frac{1}{2,000}\right)$ = 560,000 tons/year

Application of Control = 41 %

Process Emissions into Uncontrolled Plants = 330,400 tons/year

Process Emissions into Controlled Plants = 229,600 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
ESP	100	229,600

TABLE E-38

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED OPEN HEARTH FURNACES

Process - Open Hearth

Control Device - Uncontrolled

Process Emissions into Control Device 330,400 tons/year

1. Based on Particle Size Distribution in Lower Right of Figure 26.

Process Size (μ)	Emissions Percent	Control Device Uncontrolled Penetration (%) (1 - efficiency)	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	17	100		56,200
0.5-1.0	15	100		49,600
0.1-0.5	59	100		194,900
0.05-0.1	5.2	100		17,200
0.01-0.05	0.8	100		2,600
				320,500

2. Based on "Composite" Particle Size Distribution in Figure 26.

Process Size (μ)	Emissions Percent	Control Device Uncontrolled Penetration (%) (1 - efficiency)	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	22.5	100		74,300
0.5-1.0	5.3	100		17,500
0.1-0.5	2.16	100		7,100
0.05-0.1	0.04	100		100
0.01-0.05				
				99,000

TABLE E-39

FINE-PARTICLE EMISSIONS FROM OPEN HEARTH FURNACES CONTROLLED BY ELECTROSTATIC PRECIPITATOR

Process - Open Hearth

Control Device - Electrostatic Precipitator

Process Emissions into Control Device 229,600 tons/year

1. Based on Particle Size Distribution in Lower Right of Figure 26.

Process Emissions Size (μ)	Process Emissions Percent	Control Device ESP Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	17	11		4,300
0.5-1.0	15	17		5,900
0.1-0.5	59	29		39,300
0.05-0.1	5.2	41		4,900
0.01-0.05	0.8	55		1,000
				55,400

2. Based on "Composite" Particle Size Distribution in Figure 26.

Process Emissions Size (μ)	Process Emissions Percent	Control Device ESP Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	22.5	11		5,700
0.5-1.0	5.3	17		2,100
0.1-0.5	2.16	29		1,400
0.05-0.1	0.04	41		
0.01-0.05		55		
				9,200

---

[a] Efficiency values were taken from medium efficiency curve, Figure 17.

TABLE E-40

SUMMARY OF FINE-PARTICLE EMISSIONS FROM SINTER MACHINES, IRON AND STEEL PLANTS

(Tons/Year)

Source - Iron and Steel

Process - Sinter Machine--Windbox

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Cy + ESP	FF	
1-3	None		3,500	300	Neglect	3,800
0.5-1.0			1,100	100		1,200
0.1-0.5			500	100		600
0.05-0.1						
0.01-0.05						
			5,100	500		5,600

TABLE E-41

DISTRIBUTION OF PROCESS EMISSIONS FROM SINTER MACHINE

Source - Iron and Steel

Process - Sinter Machine--Windbox

	Production (tons/year)	Emission Factor (lb/ton)		
Process Emissions =	(51.0 x 10^6)	(20)	$\left(\frac{1}{2,000}\right)$	= 510,000 tons/year

Application of Control = 100 %

Process Emissions into Uncontrolled Plants = 0 tons/year

Process Emissions into Controlled Plants = 510,000 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
Cyclone	45	229,500
Cyclone + ESP	36	183,600
FF	19	96,900

TABLE E-42

FINE-PARTICLE EMISSIONS FROM SINTER MACHINES CONTROLLED BY CYCLONES

Process - Sinter Machines--Windbox

Control Device - Cyclones

Process Emissions into Control Device 229,500 tons/year

Process Size (μ)	Emissions Percent	Control Device Cyclones Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	2.7	57		3,500
0.5-1.0	0.56	82		1,100
0.1-0.5	0.23	94		500
0.05-0.1				
0.01-0.05				
				5,100

---

[a] Efficiency values were taken from high fractional efficiency curve, Figure 17.

Note: Outlet particle size distribution for sinter machines controlled by cyclones showed 20 wt. % $< 3\ \mu$. If overall efficiency of cyclones is assumed to be 80%, then quantity emitted by sinter machines controlled by cyclones is

$$(229{,}500 \text{ tons/year})\ (1-0.80)(0.20) = 9{,}200 \text{ tons/year} .$$

TABLE E-43

FINE-PARTICLE EMISSIONS FROM SINTER MACHINES CONTROLLED BY CYCLONE PLUS ELECTROSTATIC PRECIPITATOR

Process - Sinter Plant--Windbox

Control Device - Cyclone + Electrostatic Precipitator

Process Emissions into Control Device 183,600 tons/year

Process Emissions		Control Device	Control Device	
		Cyclones	ESP	
		Penetration (%)	Penetration (%)	Emissions
Size (μ)	Percent	(1 - efficiency)[a]	(1 - efficiency)[b]	(tons/year)
1-3	2.7	57	11	300
0.5-1.0	0.56	82	17	100
0.1-0.5	0.23	94	29	100
0.05-0.1				
0.01-0.05				
				500

---

[a] Efficiency values were taken from high fractional efficiency curve, Figure 17.

[b] Efficiency values were taken from medium fractional efficiency curve, Figure 17.

TABLE E-44

SUMMARY OF FINE-PARTICLE EMISSIONS FROM IRON FOUNDRY CUPOLAS
(Tons/Year)

Source - Iron Foundries

Process - Cupolas

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Scrubber	FF	
1-3	5,800		300	700		6,800
0.5-1.0	1,900		100	400		2,400
0.1-0.5	2,200		200	700		3,100
0.05-0.1	300			100		400
0.01-0.05	300			100		400
	10,500		600	2,000		13,100

TABLE E-45

DISTRIBUTION OF PROCESS EMISSIONS FROM IRON FOUNDRY CUPOLAS

Source - Iron Foundries

Process - Cupolas

Production (tons/year) Emission Factor (lb/ton)

Process Emissions = (18.0 x 10^6) (16) $\left(\frac{1}{2,000}\right)$ = 144,000 tons/year

Application of Control = 33 %

Process Emissions into Uncontrolled Plants = 96,000 tons/year

Process Emissions into Controlled Plants = 48,000 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
ESP	Neglect < 1	
Cyclone	16	7,700
Wet Scrubber	74	35,500
FF	10	4,800

TABLE E-46

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED IRON FOUNDRY CUPOLAS

Process - Cupolas

Control Device - Uncontrolled

Process Emissions into Control Device 96,000 tons/year

Process Emissions		Control Device Uncontrolled	Control Device	
Size (μ)	Percent	Penetration (%) (1 - efficiency)	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	6	100		5,800
0.5-1.0	2	100		1,900
0.1-0.5	2.3	100		2,200
0.05-0.1	0.34	100		300
0.01-0.05	0.31	100		300
				10,500

TABLE E-47

FINE-PARTICLE EMISSIONS FROM IRON FOUNDRY CUPOLAS CONTROLLED BY CYCLONES

Process - Cupolas

Control Device - Cyclones

Process Emissions into Control Device 7,700 tons/year

Process Emissions Size (μ)	Percent	Control Device Cyclones Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	6	73		300
0.5-1.0	2	89		100
0.1-0.5	2.3	100		200
0.05-0.1	0.34	100		
0.01-0.05	0.31	100		
				600

---

[a] Efficiency values were taken from medium fractional efficiency curve, Figure 17.

TABLE E-48

FINE-PARTICLE EMISSIONS FROM IRON FOUNDRY CUPOLAS CONTROLLED BY WET SCRUBBERS AND WET CAPS

Process - Cupolas

Control Device - Wet Scrubbers and Wet Caps

Process Emissions into Control Device 35,500 tons/year

Process Size (μ)	Emissions Percent	Control Device Wet Scrubber Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	6	31		700
0.5-1.0	2	61		400
0.1-0.5	2.3	86		700
0.05-0.1	0.34	99		100
0.01-0.05	0.31	100		100
				2,000

---

[a] Efficiency values were taken from low fractional efficiency curve, Figure 17.

TABLE E-49

FINE-PARTICLE EMISSIONS FROM IRON FOUNDRY CUPOLAS CONTROLLED BY FABRIC FILTERS

Process - Cupolas

Control Device - Fabric Filter

Process Emissions into Control Device 4,800 tons/year

Process Emissions		Control Device FF	Control Device	
Size (μ)	Percent	Penetration (%) (1 - efficiency)	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	6	0.5		
0.5-1.0	2	1.8		
0.1-0.5	2.3	3.3		
0.05-0.1	0.34	4.2		
0.01-0.05	0.31	4.5		
				<< 100

TABLE E-50

SUMMARY OF FINE-PARTICLE EMISSIONS FROM BARK BOILERS

(Tons/Year)

Source - Pulp Mills

Process - Bark Boiler

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Cy + ESP	FF	
1-3	17,100		32,000			49,100
0.5-1.0	3,600		8,300			11,900
0.1-0.5	1,800		4,700			6,500
0.05-0.1	100		200			300
0.01-0.05						
	22,600		45,200			67,800

TABLE E-51

DISTRIBUTION OF PROCESS EMISSIONS FROM BARK BOILER

Source - Pulp Mills

Process - Bark Boilers

Production (tons/year) — Emission Factor (lb/ton)

Process Emissions = (__________) (_____) $\left(\cancel{\frac{1}{2,000}}\right)$ = 734,400[a] tons/year

Application of Control = 72 %

Process Emissions into Uncontrolled Plants = 205,600 tons/year

Process Emissions into Controlled Plants = 528,800 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
Cyclones	100	528,800

---

[a] See Reference 1 for method of process emissions calculations.

TABLE E-52

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED BARK BOILERS

Process - Bark Boilers

Control Device - Uncontrolled

Process Emissions into Control Device 205,600 tons/year

Process Emissions Size (μ)	 Percent	Control Device Uncontrolled Penetration (%) (1 - efficiency)	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	8.3	100		17,100
0.5-1.0	1.77	100		3,600
0.1-0.5	0.89	100		1,800
0.05-0.1	0.03	100		100
0.01-0.05				
				22,600

TABLE E-53

FINE-PARTICLE EMISSIONS FROM BARK BOILERS CONTROLLED BY CYCLONES

Process - Bark Boilers

Control Device - Cyclones

Process Emissions into Control Device 528,800 tons/year

Process Emissions Size (μ)	Process Emissions Percent	Control Device Cyclones Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	8.3	73		32,000
0.5-1.0	1.77	89		8,300
0.1-0.5	0.89	100		4,700
0.05-0.1	0.03	100		200
0.01-0.05				
				45,200

---

[a] Efficiency values were taken medium fractional efficiency curve, Figure 17.

TABLE E-54

SUMMARY OF FINE-PARTICLE EMISSIONS FROM RECOVERY FURNACES
(Tons/Year)

Source - Pulp Mills

Process - Recovery Furnaces

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Cy + ESP	FF	
1-3	8,000	(See Table 77)				
0.5-1.0	4,400					
0.1-0.5	2,500					
0.05-0.1						
0.01-0.05						
	14,900					

TABLE E-55

DISTRIBUTION OF PROCESS EMISSIONS FROM RECOVERY FURNACE

Source - Pulp Mill

Process - Recovery Furnaces

Production (tons/year) Emission Factor (lb/ton)

Process Emissions = (24.3×10^6) (150) $\left(\frac{1}{2,000}\right)$ = 1,822,500 tons/year

Application of Control = 99 %

Process Emissions into Uncontrolled Plants = 18,200 tons/year

Process Emissions into Controlled Plants = 1,804,300 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
ESP	82	1,804,300 (See Note)
ESP + Wet	4	
Venturi Evaporator	11	
Venturi + Wet	3	

Note: Fractional efficiency characteristics of these specialized Venturi evaporator systems are not known. Since electrostatic precipitator represents most applications, we will assume all are equivalent to "medium" efficiency electrostatic precipitators.

TABLE E-56

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED RECOVERY FURNACES

Process - Recovery Furnace

Control Device - Uncontrolled

Process Emissions into Control Device 18,200 tons/year

Process Emissions		Control Device Uncontrolled	Control Device	
Size (μ)	Percent	Penetration (%) (1 - efficiency)	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	44	100		8,000
0.5-1.0	24	100		4,400
0.1-0.5	13.8	100		2,500
0.05-0.1	0.19	100		
0.01-0.05				
				14,900

TABLE E-57

FINE-PARTICLE EMISSIONS FROM RECOVERY FURNACES CONTROLLED BY ELECTROSTATIC PRECIPITATOR

Process - Recovery Furnace

Control Device - Electrostatic Precipitators

Process Emissions into Control Device 1,804,300 tons/year

Process Emissions Size (μ)	Percent	Control Device ESP Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	44	11		87,300
0.5-1.0	24	17		73,600
0.1-0.5	13.8	29		72,200
0.05-0.1	0.19	41		1,400
0.01-0.05		55		
				234,500

Process Emissions Size (μ)	Percent	Control Device Penetration (%) (1 - efficiency)[b]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	44	1.6		12,700
0.5-1.0	24	2.3		10,000
0.1-0.5	13.8	3.8		9,500
0.05-0.1	0.19	5.5		200
0.01-0.05				
				32,400

---

[a] Efficiency values used were taken from medium fractional efficiency curve, Figure 17.

[b] Efficiency values used were taken from high efficiency curve, Figure 17.

TABLE E-58

SUMMARY OF FINE-PARTICLE EMISSIONS FROM PULP-MILL LIME KILNS
(Tons/Year)

Source - Pulp Mills

Process - Lime Kilns

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Wet	FF	
1-3	100			1,500		1,600
0.5-1.0				200		200
0.1-0.5						
0.05-0.1						
0.01-0.05						
	100			1,700		1,800

TABLE E-59

DISTRIBUTION OF PROCESS EMISSIONS FROM PULP-MILL LIME KILNS

Source - Pulp Mills

Process - Lime Kilns

Process Emissions = (Production (tons/year) 24.3×10^6) (Emission Factor (lb/ton) 45) $\left(\frac{1}{2,000}\right)$ = 546,800 tons/year

Application of Control = 99 %

Process Emissions into Uncontrolled Plants = 5,500 tons/year

Process Emissions into Controlled Plants = 541,300 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
Wet Scrubbers	100	541,300

TABLE E-60

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED PULP-MILL LIME KILNS

Process - Lime Kiln--Pulp Mill

Control Device - Uncontrolled

Process Emissions into Control Device 5,500 tons/year

Process Emissions		Control Device Uncontrolled	Control Device	
Size (μ)	Percent	Penetration (%) (1 - efficiency)	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	1.3	100		100
0.5-1.0	0.09	100		
0.1-0.5				
0.05-0.1				
0.01-0.05				
				100

TABLE E-61

FINE-PARTICLE EMISSIONS FROM PULP-MILL LIME KILNS CONTROLLED BY WET SCRUBBERS

Process - Lime Kiln--Pulp Mill

Control Device - Wet Scrubbers

Process Emissions into Control Device 541,300 tons/year

Process Emissions		Control Device Scrubbers	Control Device	
Size (μ)	Percent	Penetration (%) (1 - efficiency)[a]	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	1.3	21		1,500
0.5-1.0	0.09	43		200
0.1-0.5		74		
0.05-0.1		95		
0.01-0.05		100		
				1,700

---

[a] Efficiency values were taken from medium efficiency curve, Figure 17.

TABLE E-62

SUMMARY OF FINE-PARTICLE EMISSIONS FROM ROTARY LIME KILNS

(Tons/Year)

Source - Lime Plant

Process - Rotary Kilns

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Wet	FF	
1-3	16,200	None	16,200	8,000	200	40,600
0.5-1.0	5,700		7,000	5,800	300	18,800
0.1-0.5	5,600		7,700	9,800	500	23,600
0.05-0.1	600		900	1,400	100	3,000
0.01-0.05	400		500	900	--	1,800
	28,500		32,300	25,900	1,100	87,800

TABLE E-63

DISTRIBUTION OF PROCESS EMISSIONS FROM ROTARY LIME KILN

Source - Lime

Process - Rotary Kilns

	Production (tons/year)	Emission Factor (lb/ton)		
Process Emissions =	(16.2×10^6)	(180)	$\left(\frac{1}{2{,}000}\right)$	=1,458,000 tons/year

Application of Control = 87 %

Process Emissions into Uncontrolled Plants = 190,000 tons/year

Process Emissions into Controlled Plants = 1,268,000 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
Cyclones	20.6	261,000
Wet	35.4	449,000
FF	44.0	558,000

TABLE E-64

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED ROTARY LIME KILNS

Process - Lime Kilns--Rotary

Control Device - Uncontrolled Plants

Process Emissions into Control Device 190,000 tons/year

Process Emissions		Control Device Uncontrolled Penetration (%) (1 - efficiency)	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
Size (μ)	Percent			
1-3	8.5	100		16,200
0.5-1.0	3.0	100		5,700
0.1-0.5	2.95	100		5,600
0.05-0.1	0.33	100		600
0.01-0.05	0.20	100		400
				28,500

TABLE E-65

FINE-PARTICLE EMISSIONS FROM ROTARY LIME KILNS CONTROLLED BY CYCLONES

Process - Rotary Lime Kilns

Control Device - Cyclone

Process Emissions into Control Device 261,000 tons/year

Process Emissions Size (μ)	Percent	Control Device Cyclone Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	8.5	73		16,200
0.5-1.0	3.0	89		7,000
0.1-0.5	2.95	100		7,700
0.05-0.1	0.33	100		900
0.01-0.05	0.20	100		500
				32,300

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[a] Efficiency values used were taken from medium fractional efficiency curve, Figure 17.

Note: Particle size distribution for kilns controlled by cyclones shows 58% $< 3\ \mu$. Therefore, assuming overall cyclone efficiency of 70%, emissions are calculated to be

$$(261{,}000 \text{ tons/year})(1-0.70)(58\%) = \underline{45{,}400 \text{ tons/ year} < 3\ \mu}.$$

TABLE E-66

FINE-PARTICLE EMISSIONS FROM ROTARY LIME KILNS CONTROLLED BY WET SCRUBBERS

Process - Rotary Lime Kilns

Control Device - Wet Scrubbers

Process Emissions into Control Device 449,000 tons/year

Process Emissions		Control Device	Control Device	
		Wet Scrubber		
Size (μ)	Percent	Penetration (%) (1 - efficiency)[a]	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	8.5	21		8,000
0.5-1.0	3.0	43		5,800
0.1-0.5	2.95	74		9,800
0.05-0.1	0.33	95		1,400
0.01-0.05	0.20	100		900
				25,900

---

[a] Efficiency values used were taken from medium efficiency curve, Figure 17.

Note: Particle size distribution for kilns controlled by wet scrubber indicates 67% < 3 μ. Assuming overall scrubber efficiency of 90%, emissions are calculated to be

(449,000 tons/year)(1-0.90)(0.67) = 30,100 tons year < 3 μ.

TABLE E-67

FINE-PARTICLE EMISSIONS FROM ROTARY LIME KILNS CONTROLLED BY FABRIC FILTER

Process - Rotary Lime Kilns

Control Device - Fabric Filter

Process Emissions into Control Device 558,000 tons/year

Process Emissions		Control Device FF	Control Device	
Size (μ)	Percent	Penetration (%) (1 - efficiency)	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	8.5	0.5		200
0.5-1.0	3.0	1.8		300
0.1-0.5	2.95	3.3		500
0.05-0.1	0.33	4.2		100
0.01-0.05	0.20	4.4		
				1,100

TABLE E-68

SUMMARY OF FINE-PARTICLE EMISSIONS FROM MUNICIPAL INCINERATORS

(Tons/Year)

Source - Municipal Incinerators

Process - Municipal Incinerators

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Wet Scrubber		
1-3	6,700		1,100	2,400[a]	200[b]	10,400
0.5-1.0	3,400		700	2,400	200	6,700
0.1-0.5	5,000		1,100	5,000	400	11,500
0.05-0.1	1,400		300	1,600	200	3,500
0.01-0.05	1,700		400	2,000	200	4,300
	18,200		3,600	13,400	1,200	36,400

---

a/ Low efficiency.

b/ Medium efficiency.

TABLE E-69

DISTRIBUTION OF PROCESS EMISSIONS FROM MUNICIPAL INCINERATOR

Source - Municipal Incineration

Process - Incinerators

Process Emissions = (Production (tons/year) 20×10^6) (Emission Factor (lb/ton) 24) $\left(\frac{1}{2,000}\right)$ = 240,000 tons/year

Application of Control = 60 %

Process Emissions into Uncontrolled Plants = 96,000 tons/year

Process Emissions into Controlled Plants = 144,000 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
Low efficiency scrubber	77	111,000
Medium efficiency scrubber	8	11,500
Cyclones	15	21,500

TABLE E-70

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED MUNICIPAL INCINERATORS

Process - Municipal Incinerator

Control Device - Uncontrolled

Process Emissions into Control Device 96,000 tons/year

Process Emissions Size (μ)	Percent	Control Device Uncontrolled Penetration (%) (1 - efficiency)	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	7.0	100		6,700
0.5-1.0	3.5	100		3,400
0.1-0.5	5.2	100		5,000
0.05-0.1	1.5	100		1,400
0.01-0.05	1.8	100		1,700
				18,200

TABLE E-71

FINE-PARTICLE EMISSIONS FROM MUNICIPAL INCINERATORS CONTROLLED BY LOW EFFICIENCY SCRUBBER

Process - Municipal Incinerator

Control Device - Low Efficiency Scrubber

Process Emissions into Control Device 111,000 tons/year

Process Emissions Size (μ)	Percent	Control Device Scrubber Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	7.0	31		2,400
0.5-1.0	3.5	61		2,400
0.1-0.5	5.2	86		5,000
0.05-0.1	1.5	99		1,600
0.01-0.05	1.8	100		2,000
				13,400

---

[a] Efficiency values were taken from low efficiency curve, Figure 17.

TABLE E-72

FINE-PARTICLE EMISSIONS FROM MUNICIPAL INCINERATOR CONTROLLED BY MEDIUM EFFICIENCY SCRUBBER

Process - Municipal Incinerator

Control Device - Medium Efficiency Scrubber

Process Emissions into Control Device 11,500 tons/year

Process Emissions Size (μ)	Process Emissions Percent	Control Device Scrubber Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	7.0	21		200
0.5-1.0	3.5	43		200
0.1-0.5	5.2	74		400
0.05-0.1	1.5	95		200
0.01-0.05	1.8	100		200
				1,200

---

[a] Efficiency values were taken from medium efficiency curve, Figure 17.

TABLE E-73

FINE-PARTICLE EMISSIONS FROM MUNICIPAL INCINERATORS CONTROLLED BY CYCLONES

Process - Municipal Incinerator

Control Device - Cyclones

Process Emissions into Control Device 21,500 tons/year

Process Emissions Size (μ)	Process Emissions Percent	Control Device Cyclone Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	7.0	73		1,100
0.5-1.0	3.5	89		700
0.1-0.5	5.2	100		1,100
0.05-0.1	1.5	100		300
0.01-0.05	1.8	100		400
				3,600

---

[a] Efficiency values were taken from medium efficiency curve, Figure 17.

TABLE E-74

SUMMARY OF FINE-PARTICLE EMISSIONS FROM ELECTRIC UTILITY PULVERIZED COAL-FIRED BOILERS
(Tons/Year)

Source - Stationary Combustion

Process - Electric Utility Pulverized Coal-Fired Boiler

Particle Size Range	Distribution of Emissions					Total
		Controlled				
(μ)	Uncontrolled	ESP	Cyclone	Cy + ESP	FF	Emissions
1-3	80,000	158,400	330,600	22,600	None	591,600
0.5-1.0	16,800	51,400	99,900	10,500		178,600
0.1-0.5	7,000	36,300	47,400	8,500		99,200
0.05-0.1	200	1,200	1,200	300		2,900
0.01-0.05						
	104,000	247,300	479,100	41,900		872,300

TABLE E-75

DISTRIBUTION OF PROCESS EMISSIONS FROM ELECTRIC UTILITY PULVERIZED COAL-FIRED BOILER

Source - Stationary Combustion

Process - Electric Utility Pulverized Coal-Fired Boiler

Process Emissions = Production (tons/year) (258.4 x 10^6) Emission Factor (lb/ton) (190) $\left(\frac{1}{2,000}\right)$ = 24.6 x 10^6 tons/year

Application of Control = 96.9 %

Process Emissions into Uncontrolled Plants = 0.8 x 10^6 tons/year

Process Emissions into Controlled Plants = 23.8 x 10^6 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
Cyclones	24.3	5.8 x 10^6
Cy + ESP	15.1	3.6 x 10^6
ESP	60.6	14.4 x 10^6

TABLE E-76

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED ELECTRIC UTILITY PULVERIZED COAL-FIRED BOILERS

Process - Electric Utility Pulverized Coal-Fired Boiler

Control Device - Uncontrolled

Process Emissions into Control Device 0.8×10^6 tons/year

Process Emissions		Control Device Uncontrolled	Control Device	
		Penetration (%)	Penetration (%)	Emissions
Size (μ)	Percent	(1 - efficiency)	(1 - efficiency)	(tons/year)
1-3	10	100		80,000
0.5-1.0	2.1	100		16,800
0.1-0.5	0.87	100		7,000
0.05-0.1	0.02	100		200
0.01-0.05				
				104,000

TABLE E-77

FINE-PARTICLE EMISSIONS FROM ELECTRIC UTILITY PULVERIZED COAL-FIRED BOILERS CONTROLLED BY ELECTROSTATIC PRECIPITATOR

Process - Electric Utility Pulverized Coal-Fired Boiler

Control Device - Electrostatic Precipitator

Process Emissions into Control Device 14.4 x 10^6 tons/year

Process Emissions		Control Device ESP	Control Device	
Size (μ)	Percent	Penetration (%) (1 - efficiency)[a]	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	10	11		158,400
0.5-1.0	2.1	17		51,400
0.1-0.5	0.87	29		36,300
0.05-0.1	0.02	41		1,200
0.01-0.05				
				247,300

---

[a] Efficiency values used were taken from average fractional efficiency curve, Figure 17.

TABLE E-78

FINE-PARTICLE EMISSIONS FROM ELECTRIC UTILITY PULVERIZED COAL-FIRED BOILERS CONTROLLED BY CYCLONES

Process - Electric Utility Pulverized Coal-Fired Boiler

Control Device - Cyclone

Process Emissions into Control Device 5.8 x 10^6 tons/year

Process Emissions Size (μ)	Process Emissions Percent	Control Device Cyclone Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	10	57		330,600
0.5-1.0	2.1	82		99,900
0.1-0.5	0.88	94		47,400
0.05-0.1	0.02	100		1,200
0.01-0.05				
				479,100

---

a/ Efficiency values used were taken from high efficiency cyclone curve, Figure 17, because power plants use higher efficiency units.

TABLE E-79

FINE-PARTICLE EMISSIONS FROM ELECTRIC UTILITY PULVERIZED COAL-FIRED BOILERS CONTROLLED BY CYCLONE PLUS ELECTROSTATIC PRECIPITATOR

Process - Electric Utility Pulverized Coal-Fired Boiler

Control Device - Cyclone + Electrostatic Precipitator

Process Emissions into Control Device 3.6×10^6 tons/year

Process Emissions Size (μ)	Process Emissions Percent	Control Device Cyclone Penetration (%) (1 - efficiency)	Control Device ESP Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	10	57	11	22,600
0.5-1.0	2.1	82	17	10,500
0.1-0.5	0.87	94	29	8,500
0.05-0.1	0.02	100	41	300
0.01-0.05				
				41,900

TABLE E-80

SUMMARY OF FINE-PARTICLE EMISSIONS FROM ELECTRIC UTILITY STOKER COAL-FIRED BOILERS

(Tons/Year)

Source - Stationary Combustion

Process - Electric Utility Stoker Coal-Fired Boiler

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Cy + ESP	FF	
1-3	4,500	900	16,300	None		21,700
0.5-1.0	800	500	4,400			5,700
0.1-0.5	300	300	1,600			2,200
0.05-0.1						--
0.01-0.05						--
	5,600	1,700	22,300			29,600

TABLE E-81

DISTRIBUTION OF PROCESS EMISSIONS FROM ELECTRIC UTILITY STOKER COAL-FIRED BOILER

Source - Stationary Combustion

Process - Electric Utility Stoker Coal-Fired Boiler

Production (tons/year) Emission Factor (lb/ton)

Process Emissions = (9.9 x 10^6) (146) $\left(\frac{1}{2,000}\right)$ = 0.72x10^6 tons/year

Application of Control = 87 %

Process Emissions into Uncontrolled Plants = 0.093 x 10^6 tons/year

Process Emissions into Controlled Plants = 0.627 x 10^6 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
ESP	5.2	0.033 x 10^6
Cyclones	94.8	0.594 x 10^6

TABLE E-82

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED ELECTRIC UTILITY STOKER COAL-FIRED BOILERS

Process - Electric Utility Stoker Coal-Fired Boiler

Control Device - Uncontrolled

Process Emissions into Control Device 0.093 x 10^6 tons/year

		Control Device	Control Device	
		Uncontrolled		
Process Size (μ)	Emissions Percent	Penetration (%) (1 - efficiency)	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	4.8	100		4,500
0.5-1.0	0.9	100		800
0.1-0.5	0.29	100		300
0.05-0.1				
0.01-0.05				
				5,600

TABLE E-83

FINE-PARTICLE EMISSIONS FROM ELECTRIC UTILITY STOKER COAL-FIRED BOILERS CONTROLLED BY ELECTROSTATIC PRECIPITATOR

Process - Electric Utility Stoker Coal-Fired Boiler

Control Device - Electrostatic Precipitator

Process Emissions into Control Device 0.033×10^6 tons/year

Process Emissions		Control Device ESP	Control Device	
Size (μ)	Percent	Penetration (%) (1 - efficiency)[a]	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	4.8	11		900
0.5-1.0	0.9	17		500
0.1-0.5	0.29	29		300
0.05-0.1				
0.01-0.05				
				1,700

---

[a] Efficiency values used were taken from average fractional efficiency curve, Figure 17.

TABLE E-84

FINE-PARTICLE EMISSIONS FROM ELECTRIC UTILITY STOKER COAL-FIRED BOILERS CONTROLLED BY CYCLONES

Process - Electric Utility Stoker Coal-Fired Boiler

Control Device - Cyclones

Process Emissions into Control Device 0.594×10^6 tons/year

Process Emissions Size (μ)	Process Emissions Percent	Control Device Cyclone Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	4.8	57		16,300
0.5-1.0	0.9	82		4,400
0.1-0.5	0.29	94		1,600
0.05-0.1				
0.01-0.05				
				22,300

---

a/ Efficiency values used were taken from high efficiency cyclone curve, Figure 17, because power plants use higher efficiency units.

TABLE E-85

SUMMARY OF FINE-PARTICLE EMISSIONS FROM ELECTRIC UTILITY CYCLONE COAL-FIRED BOILERS

(Tons/Year)

Source - Stationary Combustion

Process - Electric Utility Cyclone Coal-Fired Boiler

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Cy + ESP	FF	
1-3	32,600	7,100	8,500	None	None	48,200
0.5-1.0	8,100	2,700	3,100			13,900
0.1-0.5	3,600	2,100	1,600			7,300
0.05-0.1	100	100				200
0.01-0.05						
	44,400	12,000	13,200			69,600

TABLE E-86

DISTRIBUTION OF PROCESS EMISSIONS FROM ELECTRIC UTILITY CYCLONE COAL-FIRED BOILER

Source - Stationary Combustion

Process - Electric Utility Cyclone Coal-Fired Boiler

	Production (tons/year)	Emission Factor (lb/ton)		
Process Emissions =	(28.7 x 10^6)	(35)	$\left(\frac{1}{2,000}\right)$	= 0.51 x 10^6 tons/year

Application of Control = 71 %

Process Emissions into Uncontrolled Plants = 0.148 x 10^6 tons/year

Process Emissions into Controlled Plants = 0.362 x 10^6 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
ESP	81.2	0.294 x 10^6
Cyclones	18.8	0.068 x 10^6

TABLE E-87

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED ELECTRIC UTILITY CYCLONE COAL-FIRED BOILERS

Process - Electric Utility Cyclone Coal-Fired Boiler

Control Device - Uncontrolled

Process Emissions into Control Device 0.148×10^6 tons/year

Process Emissions		Control Device Uncontrolled Penetration (%) (1 - efficiency)	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
Size (μ)	Percent			
1-3	22	100		32,600
0.5-1.0	5.5	100		8,100
0.1-0.5	2.44	100		3,600
0.05-0.1	0.05	100		100
0.01-0.05				
				44,400

TABLE E-88

FINE-PARTICLE EMISSIONS FROM ELECTRIC UTILITY CYCLONE COAL-FIRED BOILERS CONTROLLED BY ELECTROSTATIC PRECIPITATOR

Process - Electric Utility Cyclone Coal-Fired Boiler

Control Device - Electrostatic Precipitator

Process Emissions into Control Device 0.294×10^6 tons/year

Process Emissions Size (μ)	Process Emissions Percent	Control Device ESP Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	22	11		7,100
0.5-1.0	5.5	17		2,700
0.1-0.5	2.44	29		2,100
0.05-0.1	0.05	41		100
0.01-0.05				
				12,000

---

[a] Efficiency values used were taken from average fractional efficiency curve, Figure 17.

TABLE E-89

FINE-PARTICLE EMISSIONS FROM ELECTRIC UTILITY CYCLONE COAL-FIRED BOILERS CONTROLLED BY CYCLONE

Process - Electric Utility Cyclone Coal-Fired Boiler

Control Device - Cyclone

Process Emissions into Control Device 0.068 x 10^6 tons/year

Process Emissions		Control Device Cyclone Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
Size (μ)	Percent			
1-3	22	57		8,500
0.5-1.0	5.5	82		3,100
0.1-0.5	2.44	94		1,600
0.05-0.1	0.05	100		
0.01-0.05				
				13,200

---

[a] Efficiency values used were taken from high efficiency cyclone curve, Figure 17, because power plants use higher efficiency units.

TABLE E-90

SUMMARY OF FINE-PARTICLE EMISSIONS FROM INDUSTRIAL PULVERIZED COAL-FIRED BOILERS
(Tons/Year)

Source - Stationary Combustion

Process - Industrial Pulverized Coal-Fired Boiler

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Cy + ESP	FF	
1-3	1,500	1,100	12,500	None	None	15,100
0.5-1.0			500			500
0.1-0.5						
0.05-0.1						
0.01-0.05						
	1,500	1,100	13,000			15,600

TABLE E-91

DISTRIBUTION OF PROCESS EMISSIONS FROM INDUSTRIAL PULVERIZED COAL-FIRED BOILER

Source - Stationary Combustion

Process - Industrial Pulverized Coal-Fired Boiler

Production (tons/year) Emission Factor (lb/ton)

Process Emissions = (20×10^6) (170) $\left(\frac{1}{2,000}\right)$ = $1.7\text{x}10^6$ tons/year

Application of Control = 95.5 %

Process Emissions into Uncontrolled Plants = 0.076×10^6 tons/year

Process Emissions into Controlled Plants = 1.624×10^6 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
ESP	31	0.503×10^6
Cyclones	69	1.12×10^6

TABLE E-92

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED INDUSTRIAL PULVERIZED COAL-FIRED BOILERS

Process - Industrial Pulverized Coal-Fired Boiler

Control Device - Uncontrolled

Process Emissions into Control Device 0.076 x 10^6 tons/year

Process Emissions		Control Device Uncontrolled	Control Device	
Size (µ)	Percent	Penetration (%) (1 - efficiency)	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	1.95	100		1,500
0.5-1.0	0.05	100		
0.1-0.5				
0.05-0.1				
0.01-0.05				
				1,500

TABLE E-93

FINE-PARTICLE EMISSIONS FROM INDUSTRIAL PULVERIZED COAL-FIRED BOILERS CONTROLLED BY ELECTROSTATIC PRECIPITATOR

Process - Industrial Pulverized Coal-Fired Boiler

Control Device - Electrostatic Precipitator

Process Emissions into Control Device 0.503×10^6 tons/year

Process Emissions		Control Device ESP	Control Device	
Size (µ)	Percent	Penetration (%) (1 - efficiency)[a]	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	1.95	11		1,100
0.5-1.0	0.05	17		
0.1-0.5				
0.05-0.1				
0.01-0.05				
				1,100

---

a/ Efficiency values used were taken from average fractional efficiency curve, Figure 17.

TABLE E-94

FINE-PARTICLE EMISSIONS FROM INDUSTRIAL PULVERIZED COAL-FIRED BOILERS CONTROLLED BY CYCLONES

Process - Industrial Pulverized Coal-Fired Boiler

Control Device - Cyclones

Process Emissions into Control Device 1.12×10^6 tons/year

Process Emissions Size (μ)	Process Emissions Percent	Control Device Cyclone Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	1.95	57		12,500
0.5-1.0	0.05	82		500
0.1-0.5				
0.05-0.1				
0.01-0.05				
				13,000

---

a/ Efficiency values used were taken from high efficiency cyclone curve, Figure 17.

TABLE E-95

SUMMARY OF FINE-PARTICLE EMISSIONS FROM INDUSTRIAL STOKER COAL-FIRED BOILERS
(Tons/Year)

Source - Stationary Combustion

Process - Industrial Stoker Coal-Fired Boiler

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
	Uncontrolled	Controlled				
		ESP	Cyclone	Cy + ESP	FF	
1-3	31,100	800	24,700			56,600
0.5-1.0	3,400	100	3,800			7,300
0.1-0.5	900		1,200			2,100
0.05-0.1						
0.01-0.05						
	35,400	900	29,700			66,000

TABLE E-96

DISTRIBUTION OF PROCESS EMISSIONS FROM INDUSTRIAL STOKER COAL-FIRED BOILERS

Source - Stationary Combustion

Process - Industrial Stoker Coal-Fired Boilers

Production (tons/year) Emission Factor (lb/ton)

Process Emissions = (70×10^6) (133) $\left(\frac{1}{2,000}\right)$ = 4.655×10^6 tons/year

Application of Control = 62 %

Process Emissions into Uncontrolled Plants = 1.77×10^6 tons/year

Process Emissions into Controlled Plants = 2.886×10^6 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
ESP	14.8	0.427×10^6
Cyclones	85.2	2.46×10^6

TABLE E-97

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED INDUSTRIAL STOKER COAL-FIRED BOILERS

Process - Industrial Stoker Coal-Fired Boiler

Control Device - Uncontrolled

Process Emissions into Control Device 1.77 x 10^6 tons/year

Process Emissions Size (μ)	Percent	Control Device Uncontrolled Penetration (%) (1 - efficiency)	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	1.76	100		31,100
0.5-1.0	0.19	100		3,400
0.1-0.5	0.05	100		900
0.05-0.1				
0.01-0.05				
				35,400

TABLE E-98

FINE-PARTICLE EMISSIONS FROM INDUSTRIAL STOKER COAL-FIRED BOILERS CONTROLLED BY ELECTROSTATIC PRECIPITATOR

Process - Industrial Stoker Coal-Fired Boiler

Control Device - Electrostatic Precipitator

Process Emissions into Control Device 0.427 x 10^6 tons/year

Process Emissions Size (μ)	Process Emissions Percent	Control Device ESP Penetration (%) (1 - efficiency)[a]	Control Device Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	1.76	11		800
0.5-1.0	0.19	17		100
0.1-0.5	0.05	29		
0.05-0.1				
0.01-0.05				
				900

---

[a] Efficiency values used were taken from average fractional efficiency curve, Figure 17.

TABLE E-99

FINE-PARTICLE EMISSIONS FROM INDUSTRIAL STOKER COAL-FIRED BOILERS CONTROLLED BY CYCLONES

Process - Industrial Stoker Coal-Fired Boiler

Control Device - Cyclone

Process Emissions into Control Device 2.459×10^6 tons/year

Process Emissions Size (μ)	Percent	Control Device: Cyclone Penetration (%) (1 - efficiency)[a]	Control Device: Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	1.76	57		24,700
0.5-1.0	0.19	82		3,800
0.1-0.5	0.05	94		1,200
0.05-0.1				
0.01-0.05				
				29,700

---

[a] Efficiency values were taken from high efficiency cyclone curve, Figure 17.

TABLE E-100

SUMMARY OF FINE-PARTICLE EMISSIONS FROM INDUSTRIAL CYCLONE COAL-FIRED BOILERS

(Tons/Year)

Source - Stationary Combustion

Process - Industrial Cyclone Coal-Fired Boiler

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Cy + ESP	FF	
1-3	3,200	2,000	8,300			13,500
0.5-1.0	1,200	1,100	4,400			6,700
0.1-0.5	600	1,000	2,500			4,100
0.05-0.1			100			100
0.01-0.05						
	5,000	4,100	15,300			24,400

TABLE E-101

DISTRIBUTION OF PROCESS EMISSIONS FROM INDUSTRIAL CYCLONE COAL-FIRED BOILER

Source - Stationary Combustion

Process - Industrial Cyclone Coal-Fired Boiler

Production (tons/year) Emission Factor (lb/ton)

Process Emissions = $(10 \times 10^6)\ (31)\ \left(\frac{1}{2{,}000}\right) = 0.155 \times 10^6$ tons/year

Application of Control = 91 %

Process Emissions into Uncontrolled Plants = 0.014×10^6 tons/year

Process Emissions into Controlled Plants = 0.141×10^6 tons/year

Type of Control Device	% Application on Controlled Plants	Process Emissions into Control Device (tons/year)
ESP	55	0.078×10^6
Cyclones	45	0.063×10^6

TABLE E-102

FINE-PARTICLE EMISSIONS FROM UNCONTROLLED INDUSTRIAL CYCLONE COAL-FIRED BOILERS

Process - Industrial Cyclone Coal-Fired Boiler

Control Device - Uncontrolled

Process Emissions into Control Device 0.014×10^6 tons/year

Process Emissions		Control Device Uncontrolled Penetration (%)	Control Device Penetration (%)	Emissions
Size (μ)	Percent	(1 - efficiency)	(1 - efficiency)	(tons/year)
1-3	23	100		3,200
0.5-1.0	8.5	100		1,200
0.1-0.5	4.3	100		600
0.05-0.1	0.16	100		
0.01-0.05	0.04	100		
				5,000

TABLE E-103

FINE-PARTICLE EMISSIONS FROM INDUSTRIAL CYCLONE COAL-FIRED BOILERS CONTROLLED BY ELECTROSTATIC PRECIPITATOR

Process - Industrial Cyclone Coal-Fired Boiler

Control Device - Electrostatic Precipitators

Process Emissions into Control Device 0.078×10^6 tons/year

Process Emissions		Control Device	Control Device	
		ESP		
Size (μ)	Percent	Penetration (%) (1 - efficiency)[a]	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	23	11		2,000
0.5-1.0	8.5	17		1,100
0.1-0.5	4.3	29		1,000
0.05-0.1	0.16	41		
0.01-0.05	0.04	55		
				4,100

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[a] Efficiency values used were taken from average fractional efficiency curve, Figure 17.

TABLE E-104

FINE-PARTICLE EMISSIONS FROM INDUSTRIAL CYCLONE COAL-FIRED BOILERS CONTROLLED BY CYCLONES

Process - Industrial Cyclone Coal-Fired Boiler

Control Device - Cyclones

Process Emissions into Control Device 0.063 x 10^6 tons/year

Process Emissions		Control Device Cyclone	Control Device	
Size (μ)	Percent	Penetration (%) (1 - efficiency)[a]	Penetration (%) (1 - efficiency)	Emissions (tons/year)
1-3	23	57		8,300
0.5-1.0	8.5	82		4,400
0.1-0.5	4.3	94		2,500
0.05-0.1	0.16	100		100
0.01-0.05	0.04	100		
				15,300

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a/ Efficiency values were taken from high efficiency cyclone curve, Figure 17.

TABLE E-105

SUMMARY OF FINE-PARTICLE EMISSIONS FROM ELECTRIC UTILITY AND INDUSTRIAL OIL-FIRED BOILERS
(Tons/Year)

Source - Stationary Combustion

Process - Electric Utility Oil-Fired Boiler

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
	Uncontrolled	Controlled				
		ESP	Cyclone	Cy + ESP	FF	
1-3	126,900[a]	None	None	None	None	126,900
0.5-1.0						
0.1-0.5						
0.05-0.1						
0.01-0.05						
						126,900

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[a] No accurate particle size or net control data; assumed that process emissions are 90% < 3 μ and all plants uncontrolled.

TABLE E-106

SUMMARY OF FINE-PARTICLE EMISSIONS FROM ELECTRIC UTILITY AND INDUSTRIAL GAS-FIRED BOILERS

(Tons/Year)

Source - Stationary Combustion

Process - Electric Utility Gas and LPG-Fired Boilers

Particle Size Range (μ)	Distribution of Emissions					Total Emissions
		Controlled				
	Uncontrolled	ESP	Cyclone	Cy + ESP	FF	
1-3	97,200[a]	None	None	None	None	97,200
0.5-1.0						
0.1-0.5						
0.05-0.1						
0.01-0.05						
						97,200

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[a] No accurate particle size or net control data; assumed that process emissions are 90% < 3 μ and all plants uncontrolled.